(54) Title: PHOTON TRANSISTORS
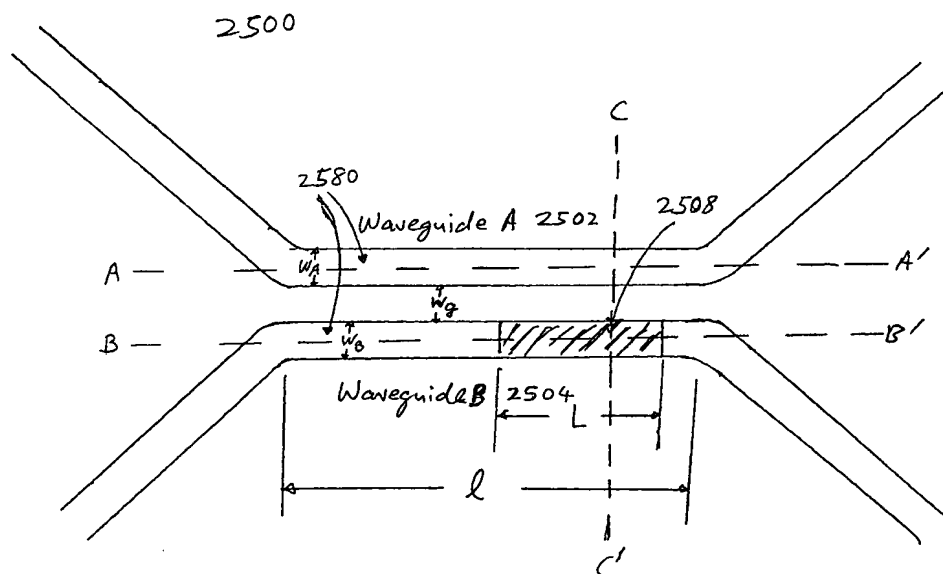
(57) Abstract: A light transfer device is provided that includes a first light pathway (1502) having a first input and a first output and a second light pathway (1504) having a second output. The second light pathway is coupled to the first light pathway, and light from the first input is transferable between the first and second light pathways. An active medium (1508) is positioned along one of the first and second light pathways, and the active medium (1508) is capable of receiving optical energy that modifies the active medium so that the active medium (1508) controls the transfer of light between the first and second pathways (1502, 1504).

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PHOTON TRANSISTORS

BACKGROUND

The present invention relates to optical devices. In particular, the present invention is related to switching devices, signal-processing devices, and logic implemented using photonic optical devices. More particularly, the present invention is related to a new class of optical devices, operated on the principle of transfer photon resistance, that are capable of performing multiple functions on signals carried by lightwaves or photons, including all-optical and electro-optical switching. The broad functionalities of these devices are similar to that of electronic transistors, except that electronic transistors operate on signals carried by RF current or electrons while the devices of the current invention operate on signals carried by lightwave or photons.

The current generation of computers utilizes a plurality of electronic transistor components. These transistors modulate the resistance to the motion of electrons (and thus current) in order to accomplish a wide variety of switching, amplification, and signal processing functions. Transistor electronic action controls or affects the motion of a stream of electrons through "transfer (electron) resistance" via the action of another stream of electrons.

Electronic transistors are typically fabricated using semiconductors such as Silicon (Si), and to a far less extent Gallium Arsenide (GaAs). Computing functions are performed by such electronic transistors integrated or grouped together as logic circuits on a very large scale with high device density. Due to various reasons discussed below, however, electronic transistor computing in present implementations is ultimately limited to the maximum data clock speeds of a few GHz. Semiconductor electronic switches generally are thought to have theoretical upper limits on their performance. Achievable minimum switching times are thought to be in the tens of picoseconds (10-20 ps), while minimum achievable switching power consumption and operational energy are thought to be around 1 microwatt (1

μW) and tens of femto-joule (10-20 fJ) levels, respectively. Such levels imply that high frequencies of operation may be possible for electronic computing.

Dense, high-frequency electronic circuit operations utilizing such electronic transistors present several persistent problems and complexities that, whether surmountable or not, are issues of concern to circuit designers. Even though electronic transistors that can operate at faster than tens of GHz do exist, the problems of electromagnetic interference (or "crosstalk"), radiation, and parasitic capacitance in dense circuits limit the clock speed of electronic computers to a range of a few GHz as the signal wavelength through the circuit becomes comparable to the circuit size. Furthermore, high-frequency electronic circuits can suffer seriously from the problems of electromagnetic interference and radiation.

It is thought that an optical circuit for which the signals are carried by light instead of electrical current may be used to eliminate the problems involving electromagnetic interference. In order for an optical circuit to perform useful computational or signal processing functions, however, there must be a way to switch optical signals using other optical signals or electrical signals. The former case is referred to as "all-optical switching" and the latter case as "electro-optical switching".

Presently, fiber-optic communication systems typically use electro-optical switching. These optical communications systems have significant advantages over electrical communications systems utilizing electronic or radio-frequency (~10^9 Hertz) circuitries, partly because of the high frequency of light (~10^{14} to 10^{15} Hertz), which allows much broader bandwidths to be used to transmit signals. However, current electro-optical switches are large in size (usually at centimeter sizes or larger) and expensive. This makes it difficult to bring the high bandwidth fiber communication systems directly to the customer's location, an undertaking which will require low-cost components capable of complex electro-optical signal processing. Thus, low-cost electro-optical devices and circuits capable of high-density of integration would be desirable. Besides optical communications, such low-cost integrated electro-optical devices and circuits can also aid in data

transmission between electronic circuits or subcircuits or within an electronic integrated circuit. A greater percentage of optical signals used in such devices would help to reduce electromagnetic radiation or interference and decrease transmission speed within each device. This could lead to improved

5   performance for high-speed electronic computers as well.

A future goal in optical communications systems is to replace part of the system with all-optical devices or circuits, which would enable faster operation. Such all-optical devices or circuits would also lead to the realization of ultrafast all-optical computers. Thus, devices that are capable of

10   electro-optical operations or a mixture of electro-optical and all-optical operations would be very desirable.

Because optical pulses can be very short (in the femtosecond range), it is often suggested that all-optical switching can be very fast. There have been attempts to construct switches that partially use light beams to switch

15   light beams in an attempt to increase speed. In such attempts, switching an optical beam with another optical beam typically involves electronics to translate an optical signal at some point to an electrical signal which is then returned back to an optical signal at a subsequent time. Optical communications systems based on such switches are not "all-optical

20   communications" because of this interface with electronic componentry. All-optical communications that allow the switching of light with light without the involvement of electronics as an intermediate step would reduce or eliminate the complexities inherent in the inclusion of electronic elements.

Below, examples of current art relating to all-optical switches as well as

25   electro-optical switches are described.

There have been various attempts to switch light with light without the use of electronics. A typical method of switching one light beam via another light beam utilizes a Mach-Zehnder interferometer with a nonlinear optical medium. This implementation may be referred to as a nonlinear optical Mach-

30   Zehnder interferometer. An exemplary Mach-Zehnder Interferometer **100** is illustrated in FIG. 1. The nonlinear optical Mach-Zehnder Interferometer **100** of FIG. 1 includes a pair of mirrors M1 **102**, M2 **104** and a pair of 50 percent

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beam splitters BS1 **106**, BS2 **108**. A Signal Beam Input **110** input into the Interferometer **100** is split into a pair of beams **112**, **114** via the 50 percent beam splitter BS1 **106**. The beams **112** and **114** are recombined at the beam splitter BS2 **108** to form a pair of resultant beams. If the beams **112** and **114** face equal optical path lengths as the beams **112** and **114** traverse the upper and lower arms, respectively, of the Interferometer **100**, then the beams **112** and **114** will constructively interfere to become Signal Beam Output A **116** and destructively interfere to become Signal Beam Output B **118**. Hence, in this event, no signal beam will be output as beam **118** (as the destructive interference cancels the power at Signal Beam Output B), while the full combined signal beam will be output as beam **116**.

A Nonlinear Refractive Index Medium **120** of length Lm, known to those skilled in the art as an optical Kerr medium, is positioned in the upper arm of the Mach-Zehnder Interferometer **100**, as shown in FIG. 1. A Control Beam Input **122** with a polarization orthogonal to that of the beam **112** is introduced via a polarization beam splitter PBS1 **124**. The Control Beam Input **122** propagates through and exits the medium **120** and is output from the Interferometer **100** via a polarization beam splitter PBS2 **126**. The medium **120** has nonlinear optical properties, in that exposing the medium **120** to a strong light beam (in this case the Control Beam Input **122**), can alter the refractive index of the medium **120**. When the Control Beam Input **122** is on, the refractive index of the medium **120** will change according to the optical intensity, which is proportional to photons per unit time per unit area, of the beam **122**. The refractive index of medium **120** can increase or decrease, which in turn causes the beam **112** in the upper arm of the Interferometer **100** to experience a change in the optical path length and to undergo an additional phase shift. This phase shift causes the destructive interference of the beams **112** and **114** at the beam splitter BS2 **108** to become constructive in forming Signal Beam Output B **118**. Similarly, the phase shift causes the constructive interference of the beams **112** and **114** at BS2 **108** to become destructive in forming the Signal Beam Output A **116**. This phenomenon leads to a net switching of signal output from the beam **116** (A) to the beam **118** (B). When

the Control Beam Input **122** is viewed as a second input signal to the Interferometer **100**, this dual input, dual-output all-optical switch can be viewed as performing optical logic operation equivalent to an "AND" gate used in the electronics realm.

The nonlinear optical Mach-Zehnder devices such as the interferometer **100** can achieve all-optical switching, but due to the lack of materials with a sufficiently high nonlinear refractive index, switches of this variety typically suffer from a number of problems and drawbacks. First, the device size (indicated by Lm in FIG. 1) is large. For a medium with a reasonably high nonlinear refractive index, a device length of 1 centimeter (1 cm) or longer is required. The large size of the device clearly prohibits their use in large-scale optical logic circuit integration. Second, the switching power required is very high, in that a control power of hundreds of Watts or more is required to operate the device at high speed. Third, while the nonlinear effect can be substantially higher when operated at close to the atomic resonance of the medium, thereby reducing the switching power, the speed of the switching operation will be slow due to real carrier excitation in the medium limiting the switching speed to below the hundreds of megahertz for a semiconductor medium. Fourth, the Mach-Zehnder device is very sensitive to device design parameter variations and vibration because of the dependence of the device on the optical path-length balance between the two arms of the interferometer.

Other variations of all-optical switching devices exist, such as one device (not shown) that uses a cavity to enhance the intensity in a medium or to achieve optical bi-stability. This device also suffers from one or more of the problems and/or drawbacks listed above with regard to the Mach-Zehnder device. These problems make the current all-optical switching devices impractical for applications to form large-scale or dense optical logic circuits. In fact it is often quite challenging to cascade even a few of the current all-optical switching devices to work together.

The nonlinear Mach-Zehnder interferometer described above and illustrated in FIG. 1 can also be implemented in a way to achieve electro-

optical switching. Such an electro-optical Mach-Zehnder interferometer has the same configuration as the nonlinear-optical Mach-Zehnder interferometer except that the Kerr Medium of the Nonlinear Refractive Index Medium **120** is replaced by an electro-optical medium known to those skilled in the art as

5   Pockel medium. The refractive index of the electro-optical medium can be altered via an applied electric field. The change in the refractive index leads to a change in the optical path length in one arm of the Mach-Zehnder interferometer, which again leads the Signal Beam Input **110** to exit the Signal Beam Output B **118** when the field is applied and to exit Signal Beam Output

10   A **116** when the field is turned off, thereby achieving electro-optical switching. The electro-optical Mach-Zehnder switch may operate within a speed range of MegaHertz to tens of GigaHertz if the nonlinear optical effect is based on an intrinsically fast physical phenomenon such as the distortion of electron clouds around the atoms. Such distortion leads to a change in the

15   microscopic electric dipole strength and in turn the macroscopic refractive index of the medium. One such medium commonly used is Lithium Niobate crystal. However, due to the smallness of such a fast electro-optic effect, a large electric field strength is needed to bring about complete switching. In typical devices, this translates into an applied voltage in the tens of volts, a

20   high voltage value for high-frequency electronics.

In addition, these devices are typically large in size, with dimensions of several centimeters. A long interaction length is needed to attain the 180 degree (or π radian) phase shift required for complete switching of the optical beam, due to the smallness of the electro-optic effect.

25   In order for computers to perform faster, and to circumvent many of the complexities that accompany electronic transistor computing at increased speeds, new compact technology must be developed. It would be advantageous to provide all-optical logic circuitry or a device family capable of improved speed, implementation at high or very high density of integration

30   (due to smaller device sizes), operation at lower switching energy and power consumption levels, and improved immunity to device variations.

SUMMARY OF THE INVENTION

In accordance with the present invention, many of the disadvantages associated with prior electrical transistor-based devices and optical beam switching devices are addressed.

In particular, the devices described herein are very small in size with typical device dimensions of a few micrometers to hundreds of nanometers and are capable of achieving optical switching and electro-optical switching at high speed and low switching energy. Using these "photonic" devices, which typically operate by manipulating photon flux, it is possible to build low-cost electro-optical optical communication systems, all-optical communication systems or all-optical logic gates that can operate at speeds of 10GHz to 10000GHz or faster. Such devices will enable the realization of computers operating with a clock rates from 10 to more than 100 times faster than that of current high-speed electronic computers. Furthermore, the compact size of the devices will allow very-high-density device integration (a few million devices per square centimeters), leading to low cost per device function and subsequently the enablement of complex operation.

In addition to their superior speed of operation, these devices are also advantageous in that the signal transfer in the photonic circuit is via an optical beam well-confined within optical waveguides. This configuration results in very little signal interference from surrounding componentry. Furthermore, optical beams do not radiate radio frequencies to cause such interference.

Like electronic transistors, these devices will have a wide range of other general applications apart from applications to computers, such as applications relating to optical communications, optical signal processing, optical sensing or quantum optical communications. For example, in optical communications, in addition to their low cost and applications to electro-optical switching, these devices will have important applications to the realization of ultrafast (Tera-bit) all-optical communications for which a stream of optical pulses is being switched at very high (Tera-Hertz) speeds directly via another stream of optical pulses without the complication and speed

compromise involved in using electronics to transfer the optical signal to an electrical signal and back again.

Unlike all the current electro-optical and all-optical switches, such as that of the Mach Zhender type described above, where the switching of light signals is activated by changing the refractive index of the active medium, the devices of the present invention enable the switching of light signals via changing the photon resistance brought about by modifying primarily the absorptive, transparency, or gain property of the active medium. It will become obvious from the exemplary devices described below that the switching of light signal based on such "transfer photon resistance" has many advantages over the current devices based on changing the refractive index of the medium. In particular, the devices of the current invention can be much smaller in size (10-10,000 times smaller), in operating power (10-1000,000 times smaller), and yet still relatively fast in switching time (hundreds of picosecond or faster). Such use of transfer photon resistance makes the devices of the current invention a close photonic analogue of electronic transistors. Hence, we call the devices of the current invention "phosistor", which is short for "photon transistors".

In one aspect of the present invention, a light transfer device is provided including a first light pathway having a first input and a first output and a second light pathway having a second output. The second light pathway is coupled to the first light pathway so that light from the first input is transferable between the first and second light pathways. An active medium is positioned along at least one of the first and second light pathways, and is capable of receiving optical energy that modifies the active medium so that the active medium controls the transfer of light between the first and second pathways.

In another aspect of the present invention, a light transfer device is provided including a first light pathway having a first input and a first output and a second light pathway having a second output. The second light pathway is coupled to the first light pathway so that light from the first input is

transferable between the first and second light pathways. An active medium is positioned along at least one of the first and second light pathways, and is capable of receiving electrical energy that modifies the active medium so that the active medium controls the transfer of light between the first and second

5   pathways.

In another aspect of the invention, a light transfer device is provided that includes a first light pathway having a first input and a first output and a second light pathway having a second output. The second light pathway is coupled to the first light pathway, and light from the first input is transferable

10   between the first and second light pathways. A third light pathway is interposed between the first and second light pathways. An active medium is positioned along at least one of the first, second and third light pathways, wherein the active medium is capable of receiving light that modifies the active medium so that the active medium controls the transfer of light between

15   the first, second and third pathways.

In yet another aspect of the invention, a light transfer component is provided having a first light pathway having a first input and a first output. A second light pathway is provided having a second output, and the second light pathway is coupled to the first light pathway. Light from the first input is

20   transferable from the first input of the first light pathway to the second output of the second light pathway. An active medium is positioned along the first light pathway. The active medium is capable of receiving electrical energy that modifies the active medium so that a substantial portion of the light from the first input no longer remains on the first light pathway.

25   The invention may be further embodied in a logic device utilizing photonic energy. In this aspect, a plurality of directional couplers are provided, wherein the directional couplers each are capable of modifying the propagation direction of a photon beam through an active medium. The active medium has light transfer control properties that are modifiable via

30   electrical energy. The directional couplers are linked by inputs and outputs

capable of transmitting the photon beam through one or more switchable propagation paths.

In yet another aspect of the invention, a light transfer device is provided having a first light pathway including a first input and a first output, a second light pathway having a second output, and a third light pathway spaced from the first light pathway and the second light pathway. The second light pathway is spaced from the first light pathway, and the third light pathway is movable between at least a first position relatively near both of the first and second light pathways and a second position relatively far from the first and second light pathways. The first position allows the first light pathway to be optically coupled with the third light pathway, and simultaneously allows the third light pathway to be optically coupled with the second light pathway.

The present invention may also be embodied in a method of manufacturing a light transfer device. The method includes the steps of etching at least two waveguide structures onto a substrate material. The waveguides each include input and output ends, and at least one of the waveguides defines a gap area between its input and output ends. An active medium is then integrated onto the substrate into the gap area using epitaxial layer growth techniques to define an active medium section of the one of the waveguides. The active medium section preferably includes a plurality of quantum wells.

In another aspect of the present invention, a method of manufacturing a waveguide structure having at least two waveguides is provided. The method includes the steps of providing a silicon dioxide substrate, bonding a layer of GaAs to the substrate, patterning a photoresist for the waveguide structures, etching the GaAs not covered by the photoresist, and etching the silicon dioxide structure so as to form an undercut.

In addition to their use as optical switches, the disclosed invention can relate to the performance of a variety of functions, including logical operations, optical flip-flops, optical wavelength translation, electro-optical switches,

optical detection, optical filtering, optical attenuation or gain, optical phase shifting, optical memory, and quantum optical operations, which take advantage of the physical effect of transfer photon resistance.

Beside their use as optical switches, the disclosed devices according to the present invention can perform a variety of multiple all-optical and electro-optical functions, including wavelength selective switching or filtering, variable optical attenuation/amplification or phase shifting, optical wavelength translation, optical diode, optical detection, optical memory, quantum-optical operations, optical flip-flops, and all-optical or electro-optical logic operations, all based on the physical effect of transfer photon resistance, which therefore creates a new class of devices. Potential applications of these devices include the realization of very-high-density photonic integrated circuits or nanoscale photonic (nanophotonic) devices and circuits, optical communications, optical sensing, optical interconnects, optical signal processing, all-optical computing, and all-optical communications.

The foregoing and other features and advantages of the presently preferred embodiments of the invention will be more readily apparent from the following detailed description, which proceeds with references to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the present invention are described with reference to the following drawings, wherein:

FIG. 1 is an illustration of an exemplary prior art Mach-Zehnder Interferometer all-optical switching device;

FIGS. 2A-C illustrate a system having essentially two energy levels used to describe an exemplary semiconductor active medium;

FIGS. 3A-C illustrate a system having essentially three energy levels used to describe an exemplary semiconductor active medium;

FIGS. 4A-D illustrate the states of a system used to describe an exemplary semiconductor active medium having essentially three energy levels and operating under two wavelengths;

FIGS. 4E-K illustrate the states of a system used to describe an exemplary semiconductor active medium operating under essentially one wavelength;

FIG. 5A illustrates an exemplary embodiment of a waveguide having an active medium made up of quantum wells;

FIG. 5B illustrates an exemplary embodiment of a waveguide having an active medium made up of quantum wells sandwiched by doped waveguide material to form a PIN junction;

FIG. 6A illustrates an embodiment of a first exemplary phosistor device utilizing directionally coupled waveguides;

FIG. 6B illustrates another embodiment of the first exemplary phosistor device gate utilizing directionally coupled waveguides and a dichroic filter;

FIG. 6C-1 is a simulation diagram illustrating the spatial distribution of the electric field strength of the first exemplary phosistor device illustrated in FIG. 6A under one exemplary state of operation out of a plurality of possible states of operation;

FIG. 6C-2 is a simulation diagram illustrating the spatial distribution of the electric field strength of the first exemplary phosistor device illustrated in FIG. 6A under another exemplary state of operation out of a plurality of possible states of operation;

FIG. 6C-3 is a simulation diagram illustrating the spatial distribution of the electric field strength of the first exemplary phosistor device illustrated in FIG. 6A under still another exemplary state of operation out of a plurality of possible states of operation;

FIG. 6D illustrates an embodiment of the first exemplary phosistor device utilizing a multi-mode interference configuration;

FIG. 6E-1 is a simulation diagram illustrating the spatial distribution of the electric field strength of the phosistor device illustrated in FIG. 6D under one exemplary state of operation out of a plurality of possible states of operation;

FIG. 6E-2 is a simulation diagram illustrating the spatial distribution of the electric field strength of the phosistor device illustrated in FIG. 6D under

another exemplary state of operation out of a plurality of possible states of operation;

FIG. 6F-1 illustrates an embodiment of the first exemplary phosistor device utilizing a first embodiment of an exemplary resonator configuration;

FIG. 6F-2 illustrates an embodiment of the first exemplary phosistor device utilizing a second embodiment of an exemplary resonator configuration;

FIG. 6F-3 illustrates an embodiment of the first exemplary phosistor device utilizing a third embodiment of an exemplary resonator configuration;

FIG. 6F-4 illustrates an embodiment of the first exemplary phosistor device utilizing a fourth embodiment of an exemplary resonator configuration;

FIG. 6G-1 illustrates an embodiment of the first exemplary phosistor device utilizing a first exemplary photonic bandgap configuration;

FIG. 6G-2 illustrates an embodiment of the first exemplary phosistor device utilizing a second exemplary photonic bandgap configuration;

FIG. 6G-3 illustrates an embodiment of the first exemplary phosistor device utilizing a third exemplary photonic bandgap configuration;

FIG. 7 illustrates an embodiment of a second exemplary phosistor device utilizing directionally coupled waveguides;

FIG. 7A-1 is a simulation diagram illustrating the spatial distribution of the electric field strength of the phosistor device illustrated in FIG. 7 under one exemplary state of operation out of a plurality of possible states of operation;

FIG. 7A-2 is a simulation diagram illustrating the spatial distribution of the electric field strength of the phosistor device illustrated in FIG. 7 under another exemplary state of operation out of a plurality of possible states of operation;

FIG. 7AA illustrates an embodiment of the second exemplary phosistor device utilizing three directionally coupled waveguides;

FIG. 7B illustrates an embodiment of the second exemplary phosistor device utilizing a multi-mode interference configuration;

FIG. 7C-1 is a simulation diagram illustrating the spatial distribution of the electric field strength of the phosistor device illustrated in FIG. 7B under

one exemplary state of operation out of a plurality of possible states of operation;

FIG. 7C-2 is a simulation diagram illustrating the spatial distribution of the electric field strength of the phosistor device illustrated in FIG. 7B under another exemplary state of operation out of a plurality of possible states of operation;

FIG. 7D-1 illustrates an embodiment of the second exemplary phosistor device utilizing a first embodiment of a first exemplary resonator configuration;

FIG. 7D-2 illustrates an embodiment of the second exemplary phosistor device utilizing a second embodiment of a first exemplary resonator configuration;

FIG. 7D-3 illustrates an embodiment of the second exemplary phosistor device utilizing a third embodiment of a first exemplary resonator configuration;

FIG. 7D-4 illustrates an embodiment of the second exemplary phosistor device utilizing a fourth embodiment of a first exemplary resonator configuration;

FIG. 7E-1 illustrates an embodiment of the second exemplary phosistor device utilizing a first embodiment of a second exemplary resonator configuration;

FIG. 7E-2 illustrates an embodiment of the second exemplary phosistor device utilizing a second embodiment of a second exemplary resonator configuration;

FIG. 7E-3 illustrates an embodiment of the second exemplary phosistor device utilizing a third embodiment of a second exemplary resonator configuration;

FIG. 7F-1 illustrates an embodiment of the second exemplary phosistor device utilizing a first exemplary photonic bandgap configuration;

FIG. 7F-2 illustrates an embodiment of the second exemplary phosistor device utilizing a second exemplary photonic bandgap configuration;

FIG. 7F-3 illustrates an embodiment of the second exemplary phosistor device utilizing a third exemplary photonic bandgap configuration;

FIG. 8A illustrates an embodiment of a third exemplary phosistor device utilizing directionally coupled waveguides;

FIG. 8B illustrates another embodiment of the third exemplary phosistor device utilizing directionally coupled waveguides and a dichroic filter;

FIG. 9 illustrates an embodiment of a fourth exemplary phosistor device utilizing directionally coupled waveguides;

FIG. 10 illustrates an embodiment of a fifth exemplary phosistor device implementing a phosistor flip-flop gate based on the second exemplary phosistor device and utilizing directionally coupled waveguides;

FIG. 11 illustrates an embodiment of a sixth exemplary phosistor device implementing a phosistor flip-flop gate based on the third exemplary phosistor device and utilizing directionally coupled waveguides;

FIG. 12 illustrates an embodiment of a seventh exemplary phosistor device implementing a phosistor optical amplifier gate based on cascading the first and second exemplary phosistor devices together and utilizing directionally coupled waveguides;

FIG. 13 illustrates an embodiment of a eighth exemplary phosistor device utilizing directionally coupled waveguides and employing electro-optics;

FIG. 14 illustrates an embodiment of a ninth exemplary phosistor device utilizing directionally coupled waveguides and employing electro-optics;

FIG. 15 illustrates an embodiment of a tenth exemplary phosistor device utilizing directionally coupled waveguides and employing electro-optics;

FIG. 16 illustrates an embodiment of a eleventh exemplary phosistor device utilizing directionally coupled waveguides and employing electro-optics;

FIGS. 17A-B are simulation diagrams illustrating the spatial distribution of the electric field strength of the eleventh exemplary phosistor device

illustrated in FIG. 16 under two exemplary possible states of operation out of a plurality of possible states of operation;

FIG. 18 illustrates an embodiment of a twelfth exemplary phosistor device utilizing directionally coupled waveguides and employing mechanical-optical principles; and

FIGS. 19A-19N illustrate a preferred embodiment of an exemplary method of fabricating waveguide and active structures.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EXEMPLARY EMBODIMENTS

CONTENTS OF DETAILED DESCRIPTION

C.   EXEMPLARY DEVICE 3

     i).   MMI/ Resonator Configuration Device

     ii).   PBG Implementation of the Coupler/ MMI/
Resonator Configuration Device

D.   EXEMPLARY DEVICE 4

     i).   Exemplary Device 4 as a Wavelength Multiplexer/
De-Multiplexer or Wavelength Selective Switch

     ii).   Multiple Waveguide Version of Device 4

     iii).   MMI/ Resonator Configuration Device

     iv).   PBG Implementation of the Coupler/ MMI/
Resonator Configuration Device

E.   EXEMPLARY DEVICE 5: A FLIP-FLOP BASED ON
EXEMPLARY DEVICE 2

     i).   The Enable State

     ii).   The Set State

     iii).   The Reset State (Enable=1; Set=0;
Reset=0$\rightarrow$1$\rightarrow$0)

     iv).   MMI/ Resonator Configuration Device

     v).   PBG Implementation of the Coupler/ MMI/
Resonator Configuration Device

F.   EXEMPLARY DEVICE 6: A FLIP-FLOP BASED ON
EXEMPLARY DEVICE 3

     i).   The Enable State

     ii).   The Set State

     iii).   The Reset State (Enable=1; Set=0;
Reset=0$\rightarrow$1$\rightarrow$0)

     iv).   MMI/ Resonator Configuration Device

     v).   PBG Implementation of the Coupler/ MMI/
Resonator Configuration Device

G.   EXEMPLARY DEVICE 7: AN OPTICAL AMPLIFIER

     i).   The First Stage (Device 1)

     ii).   The Second Stage (Device 2)

VI.   ELECTRO-OPTIC DEVICES

VII.   ADDITIONAL EXEMPLARY DEVICES AND EMBODIMENTS

      A.   EXEMPLARY DEVICE 8 (ELECTRO-OPTIC)

            i).   A First Exemplary State (State K in FIG. 4K)

            ii).   A Second Exemplary State (State H in FIG. 4H)

            iii).   A Third Exemplary State (State J in FIG. 4J)

            iv).   Exemplary Device 8 as a Switching Element

            v).   MMI/ Resonator Configuration Device

            vi).   PBG Implementation of the Coupler/ MMI/

Resonator Configuration Device

      B.   EXEMPLARY DEVICE 9 (ELECTRO-OPTIC)

            i).   A First Exemplary State (State K in FIG. 4K)

            ii).   A Second Exemplary State (State H in FIG. 4H)

            iii).   A Third Exemplary State (State J in FIG. 4J)

            iv).   Exemplary Device 9 as a Switching Element

            v).   Exemplary Device 9 as a Phase Shifter

            vi).   Exemplary Device 9 as a Wavelength Multiplexer/

De-Multiplexer or Wavelength Selective Switch

            vii).   MMI/ Resonator Configuration Device

            viii).   PBG Implementation of the Coupler/ MMI/

Resonator Configuration Device

      C.   EXEMPLARY DEVICE 10 (A THREE GATE ELECTRO-

OPTIC DEVICE)

            i).   A First Exemplary State (State K in FIG. 4K)

            ii).   A Second Exemplary State (State H in FIG. 4H)

            iii).   A Third Exemplary State (State J in FIG. 4J)

            iv).   Exemplary Device 10 as a Switching Element

            v).   Exemplary Device 10 as a Phase Shifter

            vi).   Exemplary Device 10 as a Wavelength Multiplexer/

De-Multiplexer or Wavelength Selective Switch

            vii).   MMI/ Resonator Configuration Device

I.   TERMINOLOGY

Described herein is a new class of photonic devices, referred to as "photon transistors" (or "transfer photon-resistors"). The word "resistor" is used here to describe the resistance to the motion of photons, not electrons. The photon transistor devices and the exemplary embodiments described herein present a new class of optical devices that are capable of performing multiple functions, including all-optical and electro-optical switching, wavelength selective switching or filtering, variable optical attenuation/amplification or phase shifting, optical wavelength translation, optical diode, optical detection, optical memory, quantum-optical operations, optical flip-flops, and all-optical or electro-optical logic operations. These devices are small in size, allowing very-high-density photonic integrated

circuits to be built incorporating these devices to perform complex operations, including faster optical processing or all-optical computing.

The name "photon transistor" is derived from the fact that the devices and exemplary embodiments described herein preferably use a combination

5   of means to resist or enhance the flow of photon flux in a certain direction. The modified flow of flux is preferably accomplished by altering the interference flux pattern of light and by preferably altering the light transfer control properties of the active medium via the action of another photon flux, an applied voltage or an injection current on an active medium. Preferably,

10   the interference flux pattern of light identifies, and the light transfer control property of the active medium determines, the propagation direction of the flow of photon flux in the photon transistor(s) (hereinafter "phosistor(s)") at a given time. This action is the photonic analogue of the action of an electronic transistor wherein the motion of a stream of electrons is affected or controlled

15   through "transfer resistance" via the action of another stream of electrons, or an applied voltage or injection current.

II.   THE UNDERLYING PHYSICS OF AN EXEMPLARY ACTIVE
MEDIUM

20   The photon transistor or phosistor devices and presently preferred exemplary embodiments detailed herein are based on the interaction of photons with active materials or media having multiple upper-energy levels. An example of one such active material is Gallium Arsenide Phosphide, which is used in the manufacture of conventional semiconductors. Most of the

25   phosistors and related devices herein preferably utilize two or more wavelengths of light for all-optical operations and one or more wavelengths of light for electro-optical operation under the control of an applied voltage or injection current. For the case of two wavelengths, the light beam interacting with the lower upper-energy level of the active material will have a longer

30   wavelength than that of the beam interacting with the higher upper-energy level. In general, the longest wavelength is denoted as λ_1, and all

subsequently shorter wavelengths as λ_2, λ_3, ...etc. In this notation $\lambda_1 > \lambda_2 > \lambda_3 > ...etc$. The upper-energy levels with which these wavelengths interact will be denoted by E_1, E_2, E_3...etc, respectively, with $E_1 < E_2 < E_3$...etc. If the ground-energy level for which an electron in energy level E_n can make a radiative transition to is denoted as E_{gn}, then λ_n will be related to E_n via $E_n - E_{gn} = h\nu_n$, where the frequency is $\nu_n = c/\lambda_n$, c is the speed of light in free space, and h is Planck's constant, $6.6262 \times 10^{-34} J - s$. During the transition, a photon with a quantized energy of $h\nu_n$ is either emitted or absorbed by the medium. The energy difference $E_n - E_{gn} = h\nu_n$ is referred to as the transitional energy and ν_n (λ_n) is referred to as the transitional frequency (wavelength).

Preferably, the active medium has a general ground-energy level (it can consist of a series of related ground-energy states or levels) and a number of upper-energy levels. That is, the active material or medium having multiple upper-energy levels may be defined as having multiple ground energy levels, or states. The ground-energy states are generally connected in that after an electron from an upper-energy level E_n makes a radiative transition to a ground-energy level E_{gn}, it may move, or relax, to other ground energy levels and can subsequently be excited to another upper-energy level. Thus, as far as the general operation of the active medium is concerned, the ground levels may be seen as a state reservoir holding a finite number of ground-energy electrons.

Preferably electrons excited to the upper-energy levels generally should relax back to the lower upper-energy level (often referred to as intraband relaxation) at a faster rate compared to the decay rate between an upper-energy level and the general ground-energy level (often referred to as interband decay). That is, electrons excited to the higher upper-energy level will relax rapidly to the next upper-energy level, ultimately filling the lowest upper-energy level rapidly and then continuing to fill the next higher upper-energy levels. This property is called "upper-state intraband relaxation." The

rate of upper-state relaxation is fast compared to the radiative interband decay between an upper-energy level E_n and a ground-energy level E_{gn}.

With respect to the general requirements of the active medium, three useful and exemplary active media are: (1) an essentially two-level system with a general ground-energy level and an upper-energy level; (2) an essentially three-level system with a general ground-energy level and two upper-energy levels; and (3) an essentially four-level system with a general ground-energy level and three upper-energy levels. It should be understood that these three systems are described for exemplary purposes and do not consist of or exhaust all possibilities for multi-level systems contemplated by and within the scope of the active medium utilized in the phosistor devices and embodiments described herein.

An exemplary embodiment of the active medium will be a semiconductor having a bandgap energy E_{Gap} for which the lowest upper-energy level E_1 discussed above will be the lowest state above the bandgap or lowest upper-bandgap state. Any electrons excited to above the bandgap energy will relax to the energy E_1 very rapidly (preferably in hundreds of femtoseconds or less) and will fill the states of higher upper-energy states after the lower upper-energy states have been filled. In the case of semiconductors, the higher upper-energy level E_2 discussed above can be a particular upper-bandgap state above the energy E_1. The speed of upper-state relaxation from E_2 to E_1 will depend on the energy separation between E_1 and E_2. A larger energy difference will generally slow the relaxation rate. The relaxation time is typically around hundreds of femtoseconds or less. This relaxation time is fast compared to the time it takes an electron to decay from E_1 to the ground state E_g, which is usually around a few nanoseconds to hundredths of a picosecond.

It should be understood that while a semiconductor material is a convenient active material or medium that can be used for phosistors, other media may be utilized. For example, other than semiconductor media, there

are many other atomic, molecular, ionic, or low-dimensional electronic media, such as quantum wells, quantum wires, or quantum dots, for example, that can satisfy the general requirements of the medium described and that are known to those skilled in the art.

5   For purposes of illustration and not limitation, the semiconductor material described above will be used as the exemplary active material or medium for the discussion of multi-level systems. A first, essentially two-level system having a general ground-energy level and an upper-energy level is illustrated in FIG. 2A-C. A second, essentially three-level system with a

10   general ground-energy level and two upper-energy levels is shown in FIG. 3A-C. A third, essentially four-level system with a general ground-energy level and three upper energy levels, while not illustrated, is easily extrapolated from the three level system by those skilled in the art and follows from FIGS. 3A-C and 2A-C. Again, it should be understood that these three systems are

15   described for exemplary purposes and do not consist of or exhaust all possibilities for multi-level systems contemplated by and within the scope of the active medium utilized in the phosistor devices and embodiments described herein.

         FIGS. 2A-C illustrate the case of essentially two energy levels or an

20   essentially two-level system 200 for a semiconductor active medium. FIG. 2A illustrates a single electron e_1 202 that is excited from a general ground-energy level 204 to an upper-energy level 206. FIG. 2B is a diagram illustrating the excitation of the electron e_1 202 from the general ground-energy level E_{g1} 204 to the upper-energy level E_1 206. In FIGS. 2A and 2B,

25   a zigzag dashed-line arrow 208 is used to represent the excitation from low to high energy via the absorption of light. FIG. 2C is a diagram illustrating the free spontaneous decay of the electron e_1 202 from the upper-energy level E_1 206 to the general ground-energy level E_{g1} 204. In FIG. 2C, a solid line arrow 210 is used to represent the electron decay from high to low energy while the

30   rate of this transition between E_1 206 and E_{g1} 204 is denoted by τ_{1g}.

         As described above, the general ground-energy level includes one or more electrons that can be excited to the various upper-energy levels. In

general, the transition time between any two upper-energy levels, level m (E_m) and level n (E_n), is denoted by τ_{mn} where m, n are 1,2,3…etc. and the free spontaneous decay transition rate between the upper-energy level E_m and the general ground-energy level E_g is denoted by τ_{mg}, which will be slow compared to τ_{mn}.

FIGS. 3A-C illustrate the case of essentially three energy levels or a essentially three level system **300** for a semiconductor active medium. FIG. 3A illustrates a pair of electrons e_1 **302** and e_2 **304**. The electrons **302** and **304** can be excited from a general ground-energy level **306** to a general upper-energy level **308**. As illustrated in FIGS. 3B and 3C, the essentially three-level system can be represented by four sublevels: a pair of upper-energy levels E_1 **310**, E_2 **312** with $E_1 < E_2$ and a pair of ground-energy levels E_{g1} **314**, E_{g2} **316** with $E_{g1} > E_{g2}$. The medium can thus be modeled as a collection of atoms with four energy levels. Each atom is assumed to have two electrons e_1 **302** and e_2 **304**, initially occupying the ground-energy levels E_{g1} **314** and E_{g2} **316** with $E_{g1} > E_{g2}$. In particular, FIG. 3B is a diagram illustrating the excitation of the two electrons e_1 **302** and e_2 **304** from the ground-energy levels E_{g1} **314** and E_{g2} **316**, respectively, to the upper-energy levels E_1 **310** and E_2 **312**. In FIGS. 3A and 3B, zig-zag dashed-line arrows **318** and **320** are used to represent the excitation from low to high energy of the electrons e_1 **302** and e_2 **304**, respectively.

FIG. 3C is a diagram illustrating the relaxation and transition or decay of the electrons e_1 **302** and e_2 **304** in the essentially three energy level system. When an electron (e_2 **304** for example) in E_{g2} **316** is removed from the ground-energy level (e.g. by exciting it to E_2 **312** as in FIG. 3B), the electron (e_1 **302** for example) in E_{g1} **314** will relax to fill the state at E_{g2} **316**, since the Pauli exclusion principle, as is known to those skilled in the art, allows only one electron to fill one state. Note that this can be described in the electron-hole picture of the semiconductor as a hole moving in the reverse

direction from the state E_{g2} to E_{g1}. The relaxation time between the upper-energy levels E_2 **312** and E_1 **310** is denoted by τ_{21}, while the relaxation time between the ground-energy levels E_{g1} **314** and E_{g2} **316** is denoted by τ_{g12}. In FIG. 3C, solid line arrows **322** , **324** are used to represent the free electron decay from high to low energy. The transition time between the upper-energy level E_1 **310** and E_{g1} **314** will be denoted by τ_{1g} and between the upper-energy level E_2 **312** and E_{g2} **316** will be denoted by τ_{2g}. As described above, typically τ_{21} and τ_{g12} are relatively fast with a femtosecond time scale, while τ_{1g} and τ_{2g} are relatively slow having times roughly on the scale of nanoseconds to hundreds of picoseconds.

Likewise, an essentially four-level system (not illustrated) can be represented by three upper-energy levels E_1, E_2, E_3 with $E_1 < E_2 < E_3$ and three ground-energy levels E_{g1}, E_{g2}, E_{g3} with $E_{g1} > E_{g2} > E_{g3}$, three electrons e_1, e_2, and e_3, two relaxation times τ_{21} and τ_{32} between the upper-energy levels, two relaxation times τ_{g12} and τ_{g23} between the ground-energy levels, and three free spontaneous decay transition times τ_{1g}, τ_{2g}, τ_{3g} between the upper-energy levels and the ground energy levels. While this case is not illustrated, it is easily extrapolated from the three level system by those skilled in the art and follows from FIGS. 3A-C and 2A-C.

FIGS. 4A-D illustrate several states of the essentially three-level semiconductor medium **300** described above and illustrated in FIGS. 3A-C. The active or interacting medium is typically an excitable medium. Every operating wavelength λ_1, λ_2, λ_3, ...etc. of the excitable medium in general, as opposed to just the particular case of a semiconductor active medium, can be in one of three basic states, namely (1) absorption, (2) gain, and (3) transparency, depending on the conditions of excitation. Returning to the specific case of the exemplary semiconductor active medium **300**, the medium **300** has two operating wavelengths λ_1 and λ_2, as illustrated in FIGS. 4A-D. For simplicity of illustration, and using the same nomenclature as in

FIGS. 3A-C, the system **300** is made up of two electrons, e_1 **302** and e_2 **304**. It should be understood that the two electrons, e_1 **302** and e_2 **304** are used for illustration purposes to explain and to model complex processes at a high-level. An analogous high-level model of complex processes familiar to those skilled in the art is the energy band model of electron-hole dynamics. The essentially three-level semiconductor system **300** has the pair of upper-energy levels E_1 **310**, E_2 **312** with $E_1 < E_2$ and the pair of ground-energy levels E_{g1} **314**, E_{g2} **316** typically with $E_{g1} > E_{g2}$. The case with $E_{g1} \leq E_{g2}$ may also be allowed in the case where thermal energy could help to re-distribute the ground-state electrons among the ground energy levels, thereby providing a general reservoir for ground-state electrons.

FIG. 4A illustrates the STATE OF LOSS AT λ_1 AND λ_2, the state corresponding to loss or absorption for a photon or light beam **326** at λ_1, and loss or absorption for the light beam **328** at wavelength λ_2. "Photons" are particles of light and are used interchangeably with "light" in the present description. In FIGS. 4A-D, an upwardly pointing (from low to high energy) zigzag dashed-line arrow represents loss or absorption of photons and electron excitation, a downwardly pointing (from high to low energy) zigzag dashed-line arrow represents gain of photons and electron decay, and a simultaneously upwardly and downwardly pointing zigzag dashed-line arrow represents transparency, wherein an electron has a nearly equal probability of being at the general ground-energy level **306** (see FIG. 3A) (E_{g1} **314** and E_{g2} **316**) or at the associated upper-energy level **308** (see FIG. 3A) (E_1 **310** or E_2 **312**) and photons experience neither a net gain nor a net loss. A solid arrow represents the movement of electrons. In terms of the electrons e_1 **302** and e_2 **304**, a dashed or dotted "e" represents the split location state of an electron, while transparent "e" and solid "e" represent the initial and final locations, respectively, of an electron.

As illustrated in FIG. 4A, when there are no input beams, the electrons e_1 **302** and e_2 **304** will be in the ground-energy levels E_{g1} **314** and E_{g2} **316**,

27 .

respectively. In this state, the medium **300** will be rendered into the absorption state, or in other words will become an absorbing medium for a light beam **326** having a wavelength of light at λ_1 or a light beam **328** having a wavelength of light at λ_2. When the medium **300** absorbs the photons at λ_1

5   **326** or λ_2 **328**, the electrons e_1 **302** and e_2 **304** will be excited to upper energy level E_1 **310** or E_2 **312**, respectively (represented by the zigzag dashed-line arrows). The rate of the electronic transition or photon absorption is called the "photon absorption rate" (or electron excitation rate). As is known to those skilled in the art, this transition rate is determined by the rate at which photons

10   are captured by the medium and is not limited by the slow free spontaneous decay rate. The medium **300** is said to be in the absorbing state at λ_1 **326** and λ_2 **328**. This state is illustrated in FIG. 4A.

FIG. 4B illustrates the STATE OF GAIN AT λ_1 AND LOSS AT λ_2, the state corresponding to gain for the photon or light beam **326** at λ_1 and loss for

15   the light beam **328** at wavelength λ_2. This state can be brought about photonically by an excitation of the medium **300** with a light beam **328** at λ_2 which will bring the electron e_2 **304** from the ground-energy levels (in particular E_{g2} **316**) to the upper-energy level E_2 **312**.

The electron e_2 **304** will quickly relax back to the lower upper-energy

20   level E_1 **310** (within a hundreds of femtosecond time scale for the semiconductor medium **300**). That is, the electron e_2 **304** is brought to level E_1 **310** from level E_{g2} **316** due to a light beam **328** at λ_2. An electron population inversion then occurs between level E_1 **310** and the ground-energy level E_{g1} **314** (i.e. the number of electrons in level E_1 **310** is more than that in

25   E_{g1} **314** (shown in FIG. 3A)). In this state, a light beam **326** at λ_1 will "stimulate" the decay of the electron e_2 **304** from E_1 **310** to E_{g1} **314**, enabling the medium **300** to emit a photon at a wavelength of λ_1 (not illustrated in FIG. 4B), thereby achieving energy gain for the light beam **326** at wavelength λ_1.

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This result is referred to as stimulated emission. The rate of the electronic stimulated decay or photon stimulated emission is called the photon stimulated emission rate (or electron stimulated decay rate). As is known to those skilled in the art, this transition rate is determined by the rate at which photons interact with the medium and is not limited by the slow free spontaneous emission rate. In this state illustrated in FIG. 4B, the medium **300** is said to be in the gain state at λ_1 **326**. This method of inducing the state of 4B is used often in the situation of control-beam induced gain for which a signal beam at λ_1 is made to achieve gain through a medium by inducing the medium to be in the state of gain with the intensity of a second control beam at λ_2 whose power is being absorbed by the medium.

FIG. 4C illustrates the STATE OF TRANSPARENCY AT λ_1 AND LOSS AT λ_2, the state corresponding to transparency for the light beam **326** at λ_1, and loss for the light beam **328** at wavelength λ_2. There are three main methods by which this can be brought about: (1) by a strong light beam at λ_1, (2) by a light beam at λ_2 and a strong light beam at λ_1, and (3) by a light beam at λ_2. In the case of method (1), it might appear at first that a strong light beam at λ_1 will bring about gain at λ_1. That is electron population inversion can be achieved by exciting the electron e$_1$ **302** from E_{g1} **314** to E_1 **310** directly by a light beam **326** at λ_1. This is not the case, however, for the reason that when an electron population builds up at E_1 **310**, the same light beam **326** at λ_1 will also cause the stimulated decay of the electron **302** from E_1 **310** back to E_{g1} **314**. If the intensity I_1 of the light beam **326** at λ_1 is very strong, this intensity will cause close to half-electron population inversion between E_{g1} **314** to E_1 **310**. In this instance, the photon stimulated emission rate is approximately equal to the photon absorption rate). In this state, the medium **300** will not absorb many photons from the light beam **326** at λ_1 or give much gain (cause photons to be emitted) in response to the light beam **326** at λ_1. Instead the medium **300** will act as a nearly transparent medium at

λ_1 **326**. In this state, the medium **300** is said to be in the transparency state at λ_1 **326**. As E_2 is not excited, there will be absorption at λ_2. This state is illustrated in FIG. 4C with the nearly half-populated electron e₁ **302** represented with dashed or dotted lines. This transparency state is represented with the simultaneously upward and downward pointing zigzag dashed-line arrow. The word transparency is used here not necessarily to refer to the state of zero loss but the state for which the absorption of the medium is substantially reduced and the medium is not excited to the state of substantial gain. The critical intensity that is required for the light beam **326** at wavelength λ_1 to bring about this transparency condition is called the "saturation intensity" and will be denoted as I_{1Sat}. More specifically, in this case the medium absorption coefficient α at λ_1 is a function of the intensity I_1 and is typically given by:

$$\alpha = \frac{\alpha_0}{1 + \dfrac{I_1}{I_{1Sat}}},$$

where α_0 is the absorption coefficient when the intensity I_1 is zero. That is, when $I_1 = I_{1Sat}$, the absorption of the medium **300** will reduce to about half and the absorption of medium **300** will rapidly reduce when $I_1 > I_{1Sat}$. The situation corresponding to the case of method (1) is referred to as 4C-I.

In case of method (2) for producing a transparency state, a light beam at λ₂ is present in addition to the strong light beam at λ₁ and the λ₂ light begins to excite electrons from the ground energy level E_{g2} **316** to E_2 **312**, which subsequently decay to energy level E_1 **310** and populate energy level E_1 **310**, causing close to half-electron population inversion between E_{g1} **314** and E_1 **310**. If these electrons remain at E_1 **310**, then they will prevent any further electrons from decaying from energy level E_2 **312** to E_1 **310** due to the Pauli exclusion principle. The electron population will thus begin to build up at energy level E_2 **312** as well, eventually causing the state at λ₂ to be driven to

a transparency state. However, the presence of the strong λ_1 light de-excites the electron populations at E_1 **310** rapidly to ground energy level E_{g1} **314**.

The net result is that the strong light at λ_1 prevents the build up of the electron population at energy level E_2 **312** and maintains the state at λ_2 as one of loss. This situation can be referred to as 4C-II. In the case where the light beam at λ_2 is not very strong so that the population at λ_1 decays away before it can build up substantially, it is also possible to drive the state to transparency at λ_1 but loss at λ_2 without the presence of the light beam at λ_1. This situation corresponds to the case of method (3) and can be referred to as 4C-III.

There are various ways the state of 4C induced by the three different methods is utilized in device applications. The method of 4C-I can be used in the situation of self-induced transparency for which a signal light beam at λ_1 is made to propagate through an otherwise absorbing medium by inducing the medium to be transparent with its own intensity. The method of 4C-III can be used in the situation of control-light-beam induced transparency for which a signal light beam at λ_1 is made to propagate through an otherwise absorbing medium by inducing the medium to be transparent with the intensity of a second (control) light beam at λ_2. The method of 4C-III can be used in the situation of control-light-beam induced loss for which a signal light beam at λ_2 is made not to propagate through an otherwise transparent or gain medium by inducing the medium to be absorbing with the intensity of a second (control light beam) at λ_1. In the case of such usage of 4C-II, the main effect used is the loss at λ_2, not the transparency at λ_1.

FIG. 4D illustrates the STATE OF GAIN AT λ_1 AND TRANSPARENCY AT λ_2, the state corresponding to gain for the light beam **326** at λ_1, and transparency for the light beam **328** at wavelength λ_2. This state can be brought about by a strong light beam at λ_2. Similarly to FIG. 4C, if the intensity I_2 of the light beam **328** at λ_2 is strong enough, the light beam **328** at λ_2 not only will bring electron e_2 **304** to E_1 **310**, causing gain at the light beam

326 at λ_1, it will also further drive E_2 **312** and E_{g2} **316** to transparency at λ_2 by exciting the electron e₂ **304** from E_{g2} **316** to E_2 **312** and partially filling up the electron population at E_2 **312** to about half of capacity. This situation occurs when the electron population at E_1 **310** is completely filled since the Pauli exclusion principle prevents the electrons at E_2 **312** from decaying or relaxing to E_1 **310**. This situation is illustrated in FIG. 4D. This method of inducing the state of 4D can be used in the situation of self-induced transparency for which a signal light beam at λ₂ is made to propagate through an otherwise absorbing medium by inducing the medium to be transparent with its own intensity.

It should be understood that although light beams **326** and **328** of wavelength λ_1 and λ_2 are shown in each of FIGS. 4A-D, the light beams **326** and **328** may be continuously or discontinuously applied to the medium or may be applied prior to one another or vice versa.

FIGS. 4E-K elaborate on the states illustrated in FIGS. 4A-D for the case of the active medium of an applied electric field or an injection current. As is known to those skilled in the art, excitation corresponding to FIGS 4A-D, can also be brought about via the use of a P-N (PN) or P-I-N (PIN, where I indicates an intrinsic semiconductor layer, positioned or sandwiched between a P-doped layer and an N-doped layer, which may contain quantum wells as part of the structure) junction or interfaces of materials capable of providing electron excitation via an injection current (e.g. a semiconductor-metal interface), and an injection current driven by an externally applied forward bias voltage across the PN or PIN junction. In this case, electrons from the ground energy levels (commonly known as the valence band for a semiconductor) will flow through the external circuit to the upper energy levels (commonly known as the conduction band for a semiconductor). In the cases of FIG. 4E-K, the role of one of the excitation light beams at λ_1 or λ_2 is played by such injection current or as will be seen below, in the cases of FIG. 4E and 4F, by an externally applied field which changes the absorption wavelength of

the semiconductor medium. FIGS. 4G-4K illustrate the case of a PIN junction
for which the upper energy level **340** is the conduction band for an n-doped
semiconductor, while the ground energy level **342** is the valence band for a p-
doped semiconductor. FIGS. 4G-4K are understood to be applicable not only
to the use of a PN and PIN junction but also to the use of interfaces of
materials capable of providing electron excitation via an injection current. The
energy increase of the excited electron is provided by the external voltage
source.

In the case of electrical excitation, a forward bias applied voltage V,
known to those skilled in the art as a forward bias across the PN or
PIN junction, is defined as positive voltage (V>0). As described above, the
forward bias creates an injection current into the PN (or PIN) junction resulting
in electron excitation from the ground to the upper energy level.

The injection current will begin to fill a particular upper energy level E_λ
with excited electrons, where λ is a wavelength above the bandgap
wavelength λ_{gap} of the semiconductor. In the absence of light, these excited
electrons will eventually decay back to the ground energy level via
spontaneous decay. With high enough injection current, when the rate of
electron excitation overcomes the rate of spontaneous decay at E_λ, the
medium reaches the state of transparency at λ for which there is half
population inversion between energy levels E_λ and $E_{g\lambda}$. This critical current
required to reach the transparency state is called the "transparency current" at
λ ($C_t(\lambda)$) and the associated voltage required may be denoted as $V = V\big|_{C=C_t(\lambda)}$.

In the case where the voltage is forward bias (V>O) but the injection
current is below its transparency value at wavelength λ ($C<C_t(\lambda)$), the
excitation of electrons is not enough to make the medium transparent and the
medium is in a loss state, which corresponds to the state illustrated in FIG. 4A
(the λ_1 λ_2), and is now recast as case G in FIG. 4G for which λ can be
identified either as λ_1 or λ_2 of FIG. 4A. Case G may be described as the state
of loss at λ with forward bias below transparency. When the input light or

photon beam at λ to the medium is strong enough (light beam intensity $I_\lambda > I_{sat}$), the loss medium can be driven to transparency at λ by the input light beam. This case is illustrated as case I in FIG. 4I, which corresponds to the state illustrated in FIG. 4C (the STATE OF TRANSPARENCY AT λ_1 AND LOSS AT λ_2). More specifically, it corresponds to case 4C induced by the method of 4C-I, and is now recast as the state of case I in FIG. 4I, for which λ can be identified as λ_1 of FIG. 4C. Case 4I may be described as the state of transparency at λ with forward bias below transparency.

The case when $C = C_t(\lambda)$ is the state of transparency at λ, which corresponds to the case illustrated in Fig. 4c (the state of transparency at λ_1 and loss at λ_2). More specifically, it corresponds to case 4C induced by the method of 4C-III, and is now recast as the case H in FIG. 4H, for which λ can be identified as λ_1 of FIG. 4C and electrical excitation replaces the role of λ_2 of FIG. 4C. State 4H may be described as the state of transparency at λ with forward bias at transparency.

When $V > V\big|_{C=C_t(\lambda)}$, the medium will reach a state of gain which corresponds to the state illustrated in FIG. 4B or 4D (state of gain at λ_1 and loss or transparency at λ_2), and is now recast as the state of case J (state of gain at λ_1) in FIG. 4J for which λ can be identified as λ_1 of FIG. 4B or 4D and electrical excitation replaces the role of λ_2 of FIG. 4B or 4D. State 4J may be described as the state of gain at λ with forward bias below transparency.

As is known to those skilled in the art, a reverse bias on a PIN junction will introduce an electric field across the intrinsic (I) region, which will sweep away any electron-hole pairs that are generated within the intrinsic region such as those generated due to absorption of light which excites the electrons to the upper energy level. The carriers that are swept away will form an external "photo" current, which will bring the electrons from the upper energy level, which is commonly known as the conduction band in semiconductor, through the external circuit and return it to the ground energy level, which is

commonly known as the valence band in semiconductor. Hence, the effect of a reverse voltage (V<0 in the definition of voltage polarity in FIGS. 4G-K) applied to the PIN junction is the de-excitation of excited electrons, which will maintain the active medium in a state of loss for operating wavelengths above the bandgap wavelength (the bandgap energy). This is the state closely related to the state of case 4C (the state of transparency at λ_1 and loss at λ_2) induced by the method of 4C-II and is now recast as case K in FIG. 4K, for which λ can be identified as λ_2 of FIG. 4C and the electrical de-excitation now plays the role of λ_1 o FIG. 4C. The state K may be described as the state of loss at λ with reverse bias.

As is commonly known to those skilled in the art, the bandgap energy is not an unmodifiable property of the medium but can be altered by tens of nanometers in wavelength via the following means:

(a) Franz-Keldysh Effect: The application of an electric field on a bulk semiconductor medium lowers the absorption band edge, causing light with wavelength just below the bandgap energy to go from a transparency state to a loss state. A change in the absorption band edge by about 10 nanometers, for example, can be achieved with an applied electric field of 2.3 x 10^5 Volts/meter (V/m).

(b) Quantum-Confined Stark Effect: Similar to the above effect but applied to a quantum well medium instead of a bulk medium. This effect is stronger due to the involvement of quantum well confinement of carriers.

Both of these effects can be utilized to bring a wavelength from a transparency state to a loss state via an applied field. This field can be applied without the use of a PN or PIN junction, although it can also be applied via the use of a PN or PIN junction with reverse bias (forward bias will have little field due to large current flow through the junction).

It should be understood that references in the description to the application of a voltage to bring the active medium to a state of loss can be accomplished through (i) the use of a PN or PIN junction or external circuit to de-excite any excited electrons, (ii) the shifting of the bandgap energy via an

applied electric field without the use of a PN or PIN junction, or (iii) the shifting of the bandgap energy via an applied electric field with reverse bias across a PN or PIN junction. Cases (ii) and (iii) can be described in terms of two new states specific to the electro-optic case. Specifically, in the absence of an applied field (V=0), the medium is transparent at wavelength λ, where λ is longer than the bandgap wavelength λ_{gap} ($\lambda_0 > \lambda_{gap}(V=0)$). This is illustrated as case E in FIG. 4E. The case 4E may be described as the state of transparency at λ with zero applied field.

In the presence of an applied field (V≠0), the medium is absorbing at wavelength λ due to lowering of the bandgap wavelength λ_{gap} under the influence of the applied field ($\lambda_0 > \lambda_{gap}(V=0)$, $\lambda_0 < \lambda_{gap}(V≠0)$) via the Franz-Keldysh effect or the quantum-confined Stark effect. This is illustrated as state F in FIG. 4F. This is the state closely related to state 4C (the state of transparency at λ_1 and loss at λ_2) induced by the method of 4C-II and is now recast as state F in FIG. 4F, for which λ can be identified as λ_2 of FIG. 4C and the electrical induced shift in bandgap now plays the role of λ_1 in FIG. 4C. The state 4F may be described as the state of loss at λ with an applied field to shift the bandgap. Going from state E to state F and back allows one to switch on and off the medium absorption at wavelength λ.

In cases 4E and 4F, the PN or PIN junction is either absent or does not play an active role as a Franz-Keldysh type effect or quantum-confined Stark effect is utilized to shift the bandgap wavelength λ_{gap}. FIGS. 4G-K utilize a PN or PIN junction to which electrical energy is applied and the PN or PIN junction plays an active role in changing the essential (gain, transparency, or loss) property of the medium.

It should be understood that the above exemplary states and exemplary methods of inducing or bringing about a particular state are illustrated for the purpose of describing the preferable exemplary properties of the medium and should not be taken to limit the embodiments of the devices. As is well known to those skilled in the art, there are numerous ways for which a particular state of the medium can be brought about via the actions of one

or more light beams or one or more electrical excitations applied to the medium. Furthermore, it is well known to those skilled in the art that the states of the medium form an uncountable or continuum set of states for which the illustrated exemplary finite set of states are meant only to highlight some of the exemplary properties utilized in the device operation. The illustrated finite set of states and the methods of inducing them illustrated in FIGS. 4A-4K are not meant to exhaust all the possible states of the medium useful in the exemplary embodiments of the devices.

III.   EXEMPLARY EMBODIMENTS OF THE WAVEGUIDE AND THE ACTIVE MEDIUM

FIG. 5A illustrates an exemplary embodiment of a waveguide **400** consisting of at least a waveguide core **402**. For applications to $0.8\,\mu m$ (or 800nm) wavelength range, an exemplary material for the waveguide core **402** is $Al_xGa_{1-x}As$ where the alloy composition x is equal to 0.3. For applications to $1.5\,\mu m$ (or 1500nm) wavelength range, an exemplary material for the waveguide core **402** is $In_{1-x}Ga_xAs_{1-y}P_y$ $In_{0.84}$ with x=0.16 and y=0.67. The exemplary waveguide core **402** is not limited to these core materials and other materials appropriate for guided wave action as known to those skilled in the art can be used, for example Gallium Arsenide (GaAs), Indium Phosphide (InP), Indium Aluminum Arsenide Phosphide ($In_{1-x}Al_xAs_{1-y}P_y$), other compound semiconductors, glass (SiO_2), silicon nitride (Si_3N_4), organic polymers such as PMMA (Poly-Methyl-Methacrylate), and others. It should be understood that the alloy composition and the resulting values are exemplary and the waveguide is not limited to the illustrative values. In an exemplary embodiment, the waveguide core **402** preferably has a width dimension W of 0.4 micrometers (μm) and a thickness T of 0.25 μm. It should be understood that the waveguide core **402** is not limited to these dimensions, and other widths and thicknesses can be utilized.

The waveguide core **402**, as is known to those skilled in the art, can be fabricated onto a substrate and/or be surrounded by a cladding material with a refractive index lower than the refractive index of the waveguide core. In a useful embodiment, the waveguide core **402** sits above a low refractive index material and can be surrounded from the top and/or from the sides by a similar or equivalent low refractive index material. Some examples of such a low refractive index materials are silicon dioxide SiO_2, or silicon nitride Si_3N_4, or organic polymers such as PMMA (poly-Methy-Methachrorate), or a transparent conducting oxide such as Indium Tin oxide or Zinc Indium Oxide (e.g., $Zn_xIn_yO_{x+1-5y}$), or a semiconductor with a lower refractive index than the refractive index of the waveguide core. In the presently preferred embodiment, the waveguide core **402** is surrounded with SiO_2 having refractive index n = 1.5 .

The exemplary waveguide core material has an approximate refractive index equivalent to n=3.4. Let us assume the refractive index of the cladding material surrounding the waveguide core is 1.5. As is known to those skilled in the art, these refractive indices and the waveguide thickness of 0.25 μm provide a planar-waveguide effective propagating refractive index n_{eff} of approximately 2.0 at a wavelength of 1.5 μm (or 1500nm) for a transverse magnetic wave with magnetic field polarization parallel to the waveguide width. The effective propagating refractive index n_{eff} is basically related to the phase velocity V of light propagation along the waveguide via $V = \dfrac{c}{n_{eff}}$, where c is the speed of light in vacuum. The use of such effective index allows one to simulate the 3D waveguide as an effective 2D waveguide.

It should be understood that other waveguide structures can be utilized in phosistor embodiments. Such other structures include, but are not limited to, waveguiding devices based on repeated reflection via metal surface structures, photonic-bandgap structures, as well as structures with graded or gradually varying refractive indices,

In another exemplary embodiment, waveguide **400** can include an active medium as a section of the waveguide core, as illustrated by

waveguide **430** of FIG 5B. Waveguide **430** includes an active medium **420** in section **408** of length L of the waveguide core. In a presently preferred embodiment, the exemplary active medium **420** fills or occupies the center region of the $Al_xGa_{1-x}As$ or $In_{1-x}Ga_xAs_{1-y}P_y$ waveguide core **402** for a length L, illustrated in FIG. 5B. In a useful embodiment, and as illustrated in FIG. 5C the active medium is made up of five semiconductor quantum wells. The design, fabrication and use of multi-quantum well-structures in optical devices is well known to those skilled in the art. In another embodiment, the active medium can be quantum dots, quantum wires, bulk semiconductor, rare-earth-doped (e.g. erbium-doped) semiconductor, or rare-earth-doped (e.g. erbium-doped) glass. The active medium can also be positioned in the waveguide cladding material instead of in the waveguide core.

FIG. 5C illustrates an exemplary embodiment of an active medium **420** of length L based on a multi-quantum well structure. One or more quantum wells **422** each having thickness t_q are sandwiched with and alternate with four barrier layers **424** each having thickness t_b. The number of quantum wells **422** and the number of barrier layers **424** shown in FIG. 5C are illustrative and are not limited to the stated values. The quantum wells **422** and barrier layers **424** preferably have a total thickness t_{MED} as illustrated in FIG. 5C. Preferably, the waveguide core material **402**, as illustrated in FIG. 5C serves as a top "layer" **426** and a bottom "layer" **428** for the active medium **420**.

In this exemplary embodiment, the quantum wells **422** can be formed of 10 nanometer ("nm") thick GaAs sandwiched by 10 nm thick $Al_{0.3}Ga_{0.7}As$ barriers **424** (for application to 0.8 μm wavelength range) or 10 nm thick $In_{0.53}Ga_{0.47}As$ sandwiched by 10nm thick $In_{0.84}Ga_{0.16}As_{0.33}P_{0.67}$ barrier **424** (for application to 1.5 μm wavelength range). It should be understood that the alloy compositions are not limited to these illustrative values. The total thickness for the quantum wells **422** and barrier layers **424** in this exemplary embodiment with five quantum wells preferably will be 0.09 micrometers or microns (μm). This thickness is well within an exemplary 0.25 μm thickness

dimension of waveguide core **402**. In this embodiment, the waveguide core
material 402 serving as a top "layer" **426** and a bottom "layer" **428** for the
active medium 420 is made up of $Al_{0.3}Ga_{0.7}As$ (for 0.8 μm) or

$In_{0.84}Ga_{0.16}As_{0.33}P_{0.67}$ (for 1.5 μm).

5   FIG. 5D illustrates as yet another exemplary embodiment for which
waveguide **400** includes a PIN-junction at the active medium, as illustrated by
waveguide **450** having the active medium **420** of length L based on a multi-
quantum well structure. The Waveguide **450** is the same as Waveguide **430**
of FIG. 5B except that a top "layer" **476** and a bottom "layer" **478** for the active

10   medium **420** are doped as p and n material respectively, thus forming a PIN
junction as described above with the active medium **420**. In addition, a
variable voltage source **480** having applied voltage V is placed across the PIN
junction formed by the active medium **420** and the top and bottom doped
layers **476** and **478**. As is well known to those skilled in the art, the applied

15   voltage will provide injection current to excite the active region. In the case of
reversed bias, the applied voltage will provide an electric field which can shift
the bandgap of the active region via the Franz-Keldysh effect or the quantum-
confined effect. This scheme can be used to change the absorptive property
of the medium as explained in the above section on the use of the Franz-

20   Keldysh effect or the quantum-confined effect. As explained above, the use
of PN junction is not even necessary when the Franz-Keldysh effect or the
quantum-confined effect is used. However, as is well known to those skilled
in the art, the conducting PN region will allow one to apply the voltage closer
to the active medium region, thereby resulting in a stronger field. As the P or

25   N region will be used more as a conductor, one can in fact use both N type (or
both P type) material on both sides of the active medium. Thus, in another
embodiment, no PN junction is used to apply the electric field. In another
embodiment, the material on both sides of the active medium is both N type or
P type material.

30   The method of encompassing an P or N type material above or below
the active medium is well known to those skilled in the art. In one

embodiment, these p and n material regions are part of the waveguide claddings. A specific example will be given later, at the discussion of FIG. 24.

The gain and loss coefficients can be made larger (or smaller) by using more (or fewer) quantum wells. For the preferred embodiments of the phosistor devices, the main parameters characterizing the active medium important to the main functionality of the devices are preferably the gain coefficient at full excitation, loss coefficient at full de-excitation, and the saturation intensity of the medium. The number of quantum wells and the type of active medium being used are typically variable as long as they could provide the preferred medium parameters. Typically, the gain and loss coefficients of the active medium can range from a low value when very few quantum wells are employed up to about 10 per μm when many quantum wells are employed at low temperature.

It should be understood that while a presently useful embodiment of the phosistor active medium is a multi-quantum well structure utilizing semiconductor materials, it is not the only embodiment or medium that can be utilized. Other than semiconductor media, there are many other atomic, molecular, ionic, or low-dimensional electronic media, such as other quantum wells, quantum wires, or quantum dots, for example, that can satisfy the generally preferred requirements of the medium described and that are known to those skilled in the art.

Presented below are calculations to obtain the gain coefficient g and the loss coefficient α along with discussions of the switching energies and switching times for the active medium **420** for specific light beam intensities for the various light beams in the waveguide **430 or 450**. We will show the case of $Al_xGa_{1-x}As$ based materials for applications to 0.8 μm (or 800nm) wavelength range. Calculations for the case of $In_{1-x}Ga_xAs_{1-y}P_y$ based materials or other active materials may be done in a similar manner.

Calculations and derivations were performed based on the exemplary embodiment illustrated in FIG. 5 and having illustrative dimensions described in an exemplary embodiment of waveguide **400, 430, or 450** described above.

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As described in these illustrative and exemplary calculations presented below, for the case of GaAs quantum wells, the five quantum wells at room temperature will typically provide a gain coefficient of about g=0.25 per μm when the medium **420** is fully excited for a particular operating wavelength,

5   and a loss coefficient of about $\alpha = -g = 0.5$ per μm when the medium **420** is fully de-excited and is in a loss or absorption state for a particular operating wavelength. In this exemplary embodiment of the medium **420**, the energy bandgap E_{gap} of GaAs preferably is at 870 nm, while the absorption wavelength of the quantum well is at about 820 nm.

10   Preferably, the basic elements in the active medium **420** are electron-hole pairs or excitons. Both can give rise to photon flux transfer operation.

For the case of active medium based on excitons, the number of excitons in a GaAs semiconductor quantum well such as one of the wells **422** in FIG. 5B or FIG. 5C can be estimated by the material volume divided by the

15   exciton volume. The typical diameter for an exciton in bulk GaAs is about 0.0185 μm, giving an exciton occupation volume of approximately 0.0185^3 $\mu m^3 = 6.33 \times 10^{-6} \mu m^3$. Hence in a 1 μm cubic volume, the number of excitons is about 1.6×10^5, and the exciton number density is $1.6 \times 10^5 / \mu m^3$. For the quantum well, the exciton radius can be about 1/3 to ½ smaller, giving

20   an exciton density about 8 to 27 times higher. The exciton emission width, or the spectral width of spontaneous emission from the GaAs quantum well exciton peak can be about 0.3nm at a low temperature below 77K. The dipole dephasing time can be around 1000fsec (corresponding to a spectral linewidth of 0.3nm). The carrier decay time is 3nsec, giving a spectral linewidth

25   broadening factor of about (1/F)=3nsec/1000fsec=3000. This gives a dipole dephasing rate of $\gamma_v = \gamma_{sp} /(2F) = 0.333 * 10^9 * 1500 = 0.5 * 10^{12}$. The exciton contribution to material absorption and gain can be dominating at the low temperature of 4K.

Next let us look at the case of electron-hole, which can be the

30   dominating contribution to material absorption and gain at higher temperature. When an exciton is dissociated, they become electron and hole pair. At room

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temperature, kT is about 25meV. Thus the thermal energy corresponds to a spectral width of 11.4nm. The optical energy for a single photon at 750nm wavelength is 0.264 atto-Joules (aJ), equal to $(0.264 \times 10^{-18} / 1.602 \times 10^{-19}$ eV)=1.65eV. At room temperature, before the exciton has time to decay, the exciton has already dissolved into an electron-hole pair, which decays at a slower rate. For an electron-hole population decay rate of $\gamma_{sp} = 0.333 \times 10^9 / s$ and an optical angular frequency of $2.512 \times 10^{15} / s$ (at $0.75 \mu m$), the intrinsic spectral linewidth of the electron hole is $(0.333 \times 10^9 / (2.512 \times 10^{15})$ *750nm=1×10^{-4} nm. The dipole decay rate is $\gamma_v = \gamma_{sp} / (2F)$, where F is called the dipole dephasing broadening factor. The dipole dephasing broadening factor is given by F, where (1/F)=11.4nm/1×10^{-4}nm=120000.

Next, the saturation intensity can be calculated. For exciton, the saturation intensity with $0.5*10^{12}$/sec dephasing rate is given below.

$$I_{So} = \frac{\pi \hbar \omega n^2 2\gamma_v}{3\lambda_A^2} = \frac{\pi * 0.264 * 10^{-18} * (2 * 0.5 * 10^{12}))}{3 * (0.75 * 10^{-6} / 3.4)^2} = 567 W/cm^2.$$

For the electron-hole plasma, the saturation intensity is given by:

$$I_{So} = \frac{\pi \hbar \omega n^2 2\gamma_v}{3\lambda_A^2} = \frac{\pi * 0.264 * 10^{-18} * (0.33333 * 10^9 * 120000)}{3 * (0.75 * 10^{-6} / 3.4)^2} = 22692 W/cm^2.$$

Next, the exciton and electron-hole absorption coefficients can be determined. For an exciton, the absorption cross section is given by:

$$\sigma_0 = \frac{\hbar \omega \gamma_{sp}}{2I_{so}} = \frac{0.264 * 10^{-18} * (0.33333 * 10^9)}{2 * 567} = 8.8 * 10^{-14} m^2,$$

which can also be expressed as

$$\sigma_0 = \frac{3F\lambda_A^2}{2\pi n^2},$$

$$\alpha_0 = N_e * \sigma_0 = 1.6 * 10^{17} * 2.2 * 10^{-12} = 1.4 * 10^4 / cm.$$

Experimentally, the exciton absorption coefficient is about $2 \times 10^4 / cm$. For electron-holes, the absorption cross section is given by:

$$\sigma_0 = \frac{\hbar \omega \gamma_{sp}}{2I_{so}} = \frac{0.264 * 10^{-18} * (0.3333 * 10^9)}{2 * 22000} = 2 * 10^{-15} cm^2.$$

For an electron-hole density of $3.84 \times 10^{18} / cm^3$, calculated by:

$$N_e = 1.6 * 10^{17} * \frac{12nm}{0.5nm} = 3.84 * 10^{18} / cm^3,$$

this gives an absorption coefficient of:

$$\alpha_0 = N_e * \sigma_0 = 7680 / cm.$$

Thus the absorption coefficient is approximately 10,000/cm for the electron-hole case. Below, an absorption coefficient of about 10,000/cm or 1 per μm is used. As an example, assuming an active volume of approximately 1 μm by 0.4 μm by 0.2 μm ($0.08 \mu m^3$), and a carrier density of $3.84 \times 10^6 / \mu m^3$ then the number of electron and holes will be ($0.08 * 3.84 \times 10^6$)=0.307×10^6. A medium length corresponding to the absorption length of 1 μm is used as most of the energy is expected to be absorbed in this length. This allows us to make an estimation of the saturation intensity using energy conservation that the number of electrons excited is equal to the number of photons absorbed. To fully excite all the electrons, this will require an energy of $0.264*10^{-18}*0.307*10^6$=$8.1*10^{-14}$ Joule (J) or 81 femtojoules. To achieve inversion within the natural decay time of 3nsec, it will be about 27 μW. The is, a pulse power of 27 μW will be needed. For 3psec pulses, it will be 27mW and 1psec pulses, it will be 71mW.

On the other hand, the saturation intensity of 22700W/cm^2 can be achieved with an optical power of 17 μW in a waveguide area of 0.08 μm^2. To get full inversion, twice the saturation power is needed, which will be 34 μW, agreeing with the above value of about 27 μW.

For the case of electron-hole pairs, experimentally measured transparency is achieved with 40mW power at 15 μm light beam diameter or a light beam intensity of 22KW/cm^2 (at a carrier density of about $2*10^{18}$ per cm^3). The decay rate is about 3nsec. Thus for 3nsec, the power needed in the waveguide will be 16 μW, giving for 3psec switching, a power of about 16 mW, which agrees approximately with the development above.

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With use of exciton absorption, the situation can be improved. In that case, the carrier density is $1.6*10^5$ per μm^3. The number of electron and holes in $0.5\,\mu m$ (length) by $0.2\,\mu m$ (height) by $0.4\,\mu m$ (width) volume (the length is assumed to be half of electron-hole case because of twice higher absorption) will be $0.08*0.5*1.6*10^5=0.64*10^4$. This will require an energy of $0.264*10^{-18}*1.28*10^4$ J $=1.685*10^{-15}$ J. For 3nsec pulse, the required peak power will be $0.56\,\mu W$. For 3psec, it will be 0.56mW. For 1psec, it will be 1.68mW, which is about 20-50 times smaller than that of the electron-hole case.

Below, we shall take the case of an electron hole, which can be dominating at room temperature. For device application, an important quantity is the product of gain coefficient g (or absorption coefficient -g) and the medium length. As an example, for gL = -1, the switching power will be 16mW for 3psec. The case of gL=-1 can be achieved as discussed above with the active medium filling the waveguide core ($g \approx -1/\mu m$) and with a 1 micron long medium. The typical device here requires gL=2 to 6 and gL<-6 to −50. Because of upperband filling, the gain achieved at the expected carrier number density is less than negative of the absorption coefficient of 1 per μm, or about 0.5 of the expected, which will be 0.5 per μm.

For the 5 quantum well case with $g = -0.5/\mu m$ The typical device here requires gL=2 to 6 (2 is achievable with 7.5 μm gain medium) and gL<-6 to − 50 (-6 is achievable with 15 μm absorbing medium). Because of upperband filling, the gain achieved at the expected carrier number density is less than negative of the absorption coefficient of 1 per μm, or about 0.5 of the expected, which will be 0.5 per μm.

An example of a device based on gL=2 gain medium will be a five quantum well device (0.05 μm thick) at the center of the 0.2 μm thick medium with 7.5 μm long length, giving a gain of gL= (1/2)(from 0.5 per μm)*(1/4)(from thickness ratio)*2 (from 2xenhancement at center of medium)*7.5 (from length)=2. In this five quantum well case, the effective gain coefficient is 0.25 per μm. The switching power can be obtained from the

analysis above for the 1 μm long medium case, multiplied by the larger medium volume because of the longer medium length and the reduced gain coefficient. For example, the expected switching peak power for 1 μm long gain medium with g=1per μm will be 2x of the above transparency power, which for100psec (3psec) switching will be1mW (32mW) or about 100 fJ. Thus for the case of g of two times smaller (g=0.5per μm) and a medium length of 7.5 μm here with an active medium volume of about twice larger (the medium is 4x thinner but the length is 8x longer), it will be approximately 2 times higher switching power or energy (i.e. scaling with the medium volume).

An example of a device based on gL<-6 absorbing medium will be a five quantum well device (0.05 μm thick) at the center of the 0.2 μm thick medium with 15 μm long length, giving a gain-length product of gL= -(1)(from 1 per μm)*(1/4)(from thickness ratio)*2 (from 2xenhancement at center of medium)*15 (from length)=-7.5. Low-loss switching may require gL of about - 50 achievable with 100 micron long medium length for the active medium. For the case of the medium here with gL=-6 for which the active medium is 4x thinner than the waveguide thickness and the medium length is about 15 times longer, giving an active volume that is 4 times larger then the expected transparency switching power needed will also be 4 times larger. Thus, for 3nsec/100psec/3psec switching, the switching peak power will be 64 μW /2mW/64mW or about 200femto-Joules.

With use of excitonic absorption, the switching energy can be below tens of fJ when optimized (as mentioned above, it can be 20 to 50 times lower). The narrow 0.5 nm width of the exciton peak, however, restricts the speed to slower than 3psec (150fesc for 11nm).

From the above calculations, it can be seen that the energy needed for the gain or loss gate operation is typically hundreds of femto-Joules (fJ) or so.

It should be understood that the estimated operating power given here is meant to provide an illustration of how low the switching power can be and is not meant to restrict the applications or the embodiments of the devices.

IV.   GENERAL COMMENTS ON DEVICE CLASSIFICATIONS AND OPERATIONS

As mentioned below, there are three different classes of phosistors, namely: (1) all-optical phosistors, (2) electro-optical phosistors, and (3)

5   mechanical-optical phosistors.

In most cases under discussion, light having wavelength λ_n is input to the phosistor either (1) in a continuous fashion with respect to time, that is, as continuous wave (CW) light having wavelength λ_n or (2) in a switched, or pulsed fashion with respect to time, so that pulsed light having wavelength λ_n

10   is present for the duration of the pulse, and is not substantially present otherwise (at least not at wavelength λ_n). Such pulsed light is more specifically referred to as a positively going pulsed light (light with an increased intensity during the pulse duration). In some instant, a negatively going pulsed light is of interest (light with a reduced intensity during the pulse

15   duration). When unqualified, a pulsed light is understood to be a positively going pulsed light. Such a characterization of light will be familiar to those skilled in the art. Hereafter, for simplicity of description, light or another entity "having wavelength λ_n" can be referred to as being "at λ_n."

It should be understood that in the typical operation of the phosistors,

20   including the useful embodiments described below, one or more light inputs or outputs will be described as continuous wave (CW) light. This light can otherwise take the form of pulsed light in some specific applications. It is for the purposes of illustration and not limitation that one or more light inputs or outputs will be described as continuous wave (CW) light.

25   These phosistors are also classified by their physical principles of operation. Like transistors, a phosistor can have three or more "terminals". A phosistor can involve a wave-coupling junction such as a directional coupler, or a multi-mode interference (MMI) device, or a resonator device, or a photonic bandgap structure. There are also numerous ways to confine

30   waves. As described previously, one way is through a dielectric or metallic waveguide, another way is through a photonic bandgap device. The

phosistors can be all-optical type phosistors for which electricity does not play an active role in the operation of the device (i.e. either there is no electrical input or the electrical input is used only passively to bias the active medium with a constant voltage or current). The phosistors can be electro-optical type

5   phosistors for which electrical input is an active part of the device operation (i.e. the electrical input is altered actively to affect the device output). The phosistors can also be of the mechanical-optical type for which a mechanical motion is involved in the active function of device.

           In the case of all-optical or electro-optical phosistors, it should be

10   understood that the phosistor devices and exemplary embodiments described herein use a combination of means to resist or enhance the flow of photon flux in a certain direction by preferably altering the interference flux pattern of light and by preferably altering the light transfer control properties of the active medium. Preferably, the interference flux pattern of light identifies, and the

15   light transfer control property of the active medium determines, the propagation direction of the flow of photon flux in the photon transistor(s) at a given time. For the case of optical-mechanical phosistors, the interference flux pattern of light is modified by mechanically moving a material section or a waveguide.

20   In the preferred embodiments, a coupler device transfers energy from one material region to another via interference. This interference causes the propagation direction of an input light beam to deviate from straight line propagation. In an all-optical or electro-optical phosistor, this path-changing interference is interrupted in the coupler due to an absorbing or a gain

25   medium controlled by another photon flux, an injection current or an applied voltage. This leads to an effective "transfer photon-resistance" for the spatial propagation of the original light beam by enhancing or reducing the resultant energy flux in certain regions of the coupler.

           The interference flux pattern of light is the pattern of photon flux (power

30   flow per unit area at a given spatial point) in the device, including the interaction region of the device, due to the interference effect of allowable propagating modes in the interaction region. Preferably, the interference flux

pattern of light identifies, and the light transfer control property of the active medium determines, the propagation direction of the flow of photon flux and how the energy of light propagates at various spatial locations in the photon transistor(s) at a given time. In a large spatial region, the interference flux pattern of light is reduced largely to the familiar phenomena of diffraction or Bragg reflection. In a device with a small interaction region having a size of a few or tens of optical wavelengths, depending on the device geometry, the interference flux pattern of light can take on drastically different patterns and can be altered significantly by an active medium such as the active medium **420** described previously.

It should be understood that the interference flux pattern of light is a "snapshot" of the photon flux at a particular moment in time and that several of similar patterns may exist before or after the particular moment in time that generally represent the same phenomenon. Thus, there is no one representative or unique interference flux pattern for a particular state of the phosistor device. However, interference flux patterns of light corresponding to different states are far more readily distinguishable. A particular interference flux pattern for a particular state illustrates generally the preferred overall trend or tendency of light distribution in that particular state. Therefore, for clarity, the interference flux patterns of light that correspond to a particular state of the phosistor will be referred to generally as a single overall interference flux pattern that corresponds to and is representative of that particular state, even though in the strict sense, an uncountable or continuum set of interference flux pattern of light exists that can be said to correspond to that particular state.

The state of an active medium such as active medium **420** can have influence on the interference flux patterns of light. In particular, the interference flux pattern of light when the active medium is in a state of loss is altered from the interference flux pattern of light when the medium is in a state of transparency. This is because loss can alter the mode shape, optical phase front, and the number of allowable propagating modes (usually a reduction in the number of allowable propagating modes) that can participate

in the interference. Similarly, the interference flux pattern of light when the active medium is in a state of gain is altered from the interference flux pattern of light when the medium is in a state of transparency. This is because gain can also alter the mode shape, the optical phase front, and the number of allowable propagating modes (usually an increase in the number of allowable propagating modes) that can participate in the interference. Of course, the interference flux pattern of light when the active medium is in a state of gain is altered from the interference flux pattern of light when the medium is in a state of loss, as well. It should be understood that reference to the "light transfer control properties of the active medium" and the actions of "modification" or "modifying" the "light transfer control properties" is intended to refer generally to the capabilities of an active medium such as active medium **420** when implemented with or without a PN or PIN junction (FIGS. 5B, 5C, 5D) with regard to altering the interference flux pattern of light.

V.   EXEMPLARY DEVICES AND EMBODIMENTS (ALL-OPTICAL DEVICES)

The presently preferred phosistor embodiments and devices in the case of all-optical operation may be classified by whether they convert a higher energy (lower wavelength) pulse to a lower energy (higher wavelength) pulse or vice versa, or do not convert the pulse energy at all. Presented herein are presently preferred exemplary and useful embodiments of phosistor devices utilizing wave-coupling junction such as in the form of directionally coupled waveguides based on the Waveguide **400**. In some instances, one or more arms of the directionally coupled waveguides will have an active region or medium in the form of active medium **420**. The coupling length, defined as the length to achieve maximal energy transfer from one waveguide to another, of the directional coupler involved will be denoted as ℓ_c.

A.   EXEMPLARY DEVICE 1

FIG. 6A illustrates a first general embodiment **500** of a phosistor device employing directionally coupled waveguides. The device can perform as a switching element and can in particular switch or convert a stream of slow or ultrafast (picosecond, femtosecond) optical pulses at high energy and short wavelength to a stream of slow or ultrafast optical pulses at comparatively low energy (comparatively long wavelength). The device **500** is not limited to use as a switching element and can be utilized, for example, as an all-optical logic gate, a light intensity amplifier, a photon duplicator, a light intensity modulator, a light intensity regulator, an optical phase shifter, a lossless signal tap, a quantum-nondemolition (QND) detector, and a variable optical attenuator. It should be understood that these exemplary applications of device **500** are intended to illustrate the wide range of uses for device **500**, and are not intended to limit the applications of other exemplary embodiments of device **500** to these examples. The device can be referred to as an "Input-Arm-Gain-Gate High-to-Low-Energy Phosistor" (IGHL Phosistor **500**).

IGHL Phosistor **500** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **502** and a second pathway of light consisting of the spatial region occupied by Waveguide B **504**. A third Waveguide **506** is included in Phosistor **500** for coupling an input optical pulse to the Waveguide A **502**, but which is otherwise not central to the operation of Phosistor **500**. The Waveguide A **502** preferably includes an active medium **508**. As described above, Waveguide A **502** can be implemented as waveguide **430** with active medium **420** in a useful embodiment, and waveguide B **504** and the third waveguide **506** can be implemented as waveguide **400**. The Waveguide A **502** preferably includes an input port APin1 **510**, an inner output port ASout1 **511**, and an output port ASout1a **512**. The Waveguide B **504** preferably includes an output port BPout1 **514**. The third Waveguide **506** preferably includes an input port ASin2 **516** which doubles as an output port ASout1b **524**. FIG. 6 illustrates that Waveguide A **502** has width W_A and is located at an approximately

parallel distance (coupling gap or distance) W_g from Waveguide B **504**, which has width W_B, so that a wave in Waveguide A can be coupled to a wave in Waveguide B. The terms "wave" and "light beam" are used interchangeably.

For the input port labeled "APin1" **(510)**, "P" stands for Power-Supply beam, "A" refers to Waveguide A **502**, "in" refers to **510** being an input port, and "1" refers to the input wavelength being λ_1. For the inner output port labeled "ASout1" **(511)**, "S" stands for Signal beam, "A" refers to Waveguide A **502**, "out" refers to it being an output port, "1" refers to the output wavelength being λ_1. For the output port labeled "ASout1a" **(512)**, "S" stands for Signal beam, "A" refers to Waveguide A **502**, "out" refers to it being an output port, "1" refers to the output wavelength being λ_1, and "a" is used to distinguish this port **512** which is along Waveguide A **502**. For the output port labeled "ASout1b" **(524)**, "S" stands for Signal beam, "A" refers to Waveguide A **502**, "out" refers to it being an output port, "1" refers to the output wavelength being λ_1, and "b" is used to distinguish this port **524** which is along the third Waveguide **506**. For the output port labeled "BPout1" **(514)**, "P" stands for Power-Supply beam, "B" refers to Waveguide B **504**, "out" refers to it being an output port, and "1" refers to the output wavelength being λ_1. For the input port labeled "ASin2" **(516)**, "S" stands for Signal beam, "A" refers to Waveguide A **502**, "in" refers to it being an input port, and "2" refers to the input wavelength being λ_2.

Preferably, input port APin1 **510** on the Waveguide A **502** is configured to receive continuous wave (CW) light **518** having wavelength λ_1 (at λ_1) (CW PWR IN λ_1). Under certain conditions described below when the active medium on the waveguide reaches transparency and Waveguides A and B are optically transparent, most of the CW light at λ_1 **518** propagating along the Waveguide A **502** will be transferred to Waveguide B **504** after a coupling length ℓ_c. The CW light at λ_1 **518** then exits from Waveguide B **504** at the port BPout1 **514** as continuous wave (CW) light at λ_1 (CW PWR BYPASS OUT λ_1) **520**.

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The coupling length is defined as the length at which a wave in one waveguide maximally couples into another waveguide that is coupled to the first waveguide. In this exemplary device **500**, the interaction length ℓ, defined as the length of interaction between light in Waveguides A **502** and B

5   **504** extends to approximately the full coupling length ℓ_c so that $\ell = \ell_c$. In other exemplary devices, the interaction length could be chosen to be multiple odd numbers of the coupling length ℓ_c ($\ell = 3\ell_c, 5\ell_c, 7\ell_c ...$). As is known to those skilled in the art, these coupling lengths will also achieve maximal coupling as for the case where $\ell = \ell_c$. While the choice of $\ell = \ell_c$ is illustrated

10   in this exemplary device, the interaction length may vary from the coupling length ℓ_c (or multiple odd numbers of ℓ_c) without affecting the general operating principle of the device. With the use of semiconductor materials, the interaction length ℓ may be less than 150 microns.

As shown in FIG. 6A, the length L of the active medium **508** is about

15   half the interaction length ℓ ($L \cong \frac{\ell}{2}$). Preferably, the length L of the active medium **508** may be somewhat longer or shorter than half of ℓ. Varying the length L of the active medium **508** relative to the interaction length ℓ will vary the input to output signal conversion efficiency, but will otherwise not affect the general operating principle of the device.

20   It should be understood that these dimensions and exemplary lengths are presented for purposes of illustrating a useful embodiment of the device **500** (or **550**, described below and shown in FIG. 6B) and are not intended to limit other exemplary embodiments of any exemplary device, or the device **500** (or **550**). A variety of dimensions and sizes can be used, depending on

25   the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell = \ell_c$ is illustrated in this exemplary device, other choices of interaction length can be used to achieve similar device functions.

Also, it should be understood that the shape of the waveguides do not

30   generally have to be linear. Curved shapes and different waveguide

dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an alternative location along waveguide A other than that illustrated in FIGs. 6A and 6B, and there can be more than one disconnected active medium

5   areas along waveguide A. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manners with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel or have the same widths and

10   dimensions as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of devices **500, 550** for operation at 800nm wavelength range, the wavelength λ_1 can be at 820nm, λ_2 can be at 800nm, and the Waveguide A **502** can be implemented as the Waveguide **430** illustrated in FIGS. 5B and 5C and Waveguide B **504** can be implemented

15   as the Waveguide **400** illustrated in FIG. 5A, in an $Al_xGa_{1-x}As$ embodiment for the waveguide core having alloy composition x at 0.3 giving a bandgap energy of around 690nm. Thus the core material is transparent at the wavelength λ_1 of 820nm. When the active medium is fully de-excited, the active medium absorbs light at both the 800nm and 820nm wavelengths. In

20   these embodiments, the active medium preferably is an essentially three-level medium as described in FIGs. 4A-D for which the electrons are free to relax from the upper-energy level corresponding to the 800nm absorption to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of devices **500, 550** for operation at

25   1500nm wavelength range, the wavelength λ_1 can be at 1500nm, λ_2 can be at 1480nm, and the Waveguide A **502** can be implemented as the Waveguide 430 illustrated in FIGS. 5B and 5C and Waveguide B **504** can be implemented as the Waveguide **400** illustrated in FIG. 5A, in an $In_{1-x}Ga_xAs_{1-y}P_y$ embodiment for the waveguide core having alloy compositions x=0.16 and

30   y=0.67 giving a bandgap energy of around 1100 nm. Thus the core material is transparent at the wavelength λ_1 of 1500nm. When the active medium is

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fully de-excited, the active medium absorbs light at both the 1480nm and 1500nm wavelengths. The active medium is an essentially three-level medium described in FIG. 4A-D for which the electrons are free to relax from the upper-energy level corresponding to the 1480nm absorption to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for application to the 1500nm (or 1.5 μm) wavelength range, the cross-sectional dimensions of the waveguide 400 or 430 are 0.4 μm wide by 0.25 μm thick. FIGS. 6A & 6B illustrate that Waveguide A **502** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **504**, which has width W_B. In this exemplary embodiment, the Waveguide A **502** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_g from Waveguide B **504** of 0.4 μm, while Waveguide B **504** has width W_B equal to 0.4 μm. In this exemplary embodiment for which the wavelengths of light are at around 1500nm range, ℓ_c is 15 μm.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **500, 550** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **500, 550**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i).   Exemplary Device Operation

An exemplary operation of the device 500 is described follows.

Continuous wave (CW) light having wavelength λ_1 (at λ_1) (CW PWR IN λ_1) **518** enters at the port APin1 **510** on the Waveguide A **502**. In the initial state, the active medium **508** along Waveguide A **502** is not excited and is in the state of loss analogous to Case A, as illustrated in FIG. 4A. As will be described below, the medium can also initially be in the state of transparency

analogous to Case C, as illustrated in FIG 4C. The CW light at λ_1 **518**

propagates along the Waveguide A **502** and is subsequently transferred to

Waveguide B **504** after a coupling length ℓ_c. The CW light at λ_1 **518** then

exits from Waveguide B **504** at the port BPout1 **514** as continuous wave (CW)

light at λ_1 (CW PWR BYPASS OUT λ_1) **520**.

The input port ASin2 **516** on Waveguide **506** effectively serves as

another input port of Waveguide A **502**, and is the input signal port for pulsed

light having wavelength λ_2 (SIGNAL IN λ_2) **522**. The pulsed light λ_2 **522**

entering the port ASin2 **516** will excite the active medium **508**, providing gain

at the operating wavelength λ_1 to the active medium **508** located in

Waveguide A **502**. This state of the active medium **508** is analogous to Case

B, as illustrated in FIG. 4B.

The CW light at λ_1 **518** from input port APin1 **510** then gains energy in

the active medium **508** and this extra energy at λ_1 will propagate across the

active medium to port ASout1 **511** as light beam **513** and be subsequently

divided to exit ports ASout1b **524** and ASout1a **512**. If the coupling of energy

from the port ASin2/ASout1b **516/524** to Waveguide A **502** (or equivalently to

port ASout1 **511**), is a 50/50 coupler, then the energy coupling ratio for light

propagating in the opposite direction (i.e. from port **511** to port **516/524**) will

also be 50/50. As a result, about 50 percent of λ_1 **513** at port ASout1 **511** will

go to λ_1 **526** (SIGNAL OUT λ_1) at port ASin2/ASout1b **516/524** and 50

percent of λ_1 **513** at port ASout1 **511** will go to λ_1 **528** (SIGNAL OUT λ_1) at

port ASout1a **512**.

In the case of FIG. 6A the net effect is that the pulsed light at λ_2 **522**

into port ASin2 **516** generates pulsed light at λ_1 **513** exiting waveguide section

ASout1 **511**, which proceeds to split the energy of the pulsed light λ_1 **513** to

pulsed light at λ_1 **528** exiting port ASout1a **512** and pulsed light at λ_1 **526**

exiting port ASout1b **524**. While not essential for the basic operation of the

device **500**, an improved version **550** of the device **500** can be achieved via

using a frequency-selective coupler such as grating or a small resonator.

Such a frequency dependent coupler is called a dichroic filter or coupler and is shown as part of device **550** in FIG. 6B, replacing Waveguide **506** of FIG. 6A. The dichroic filter **556** will couple most of the pulsed light λ_2 **572** entering the port ASin2 **566** to Waveguide A **502** but not λ_1. In this case, most of λ_1 (SIGNAL OUT λ_1) **578** will not couple from Waveguide A **502** to the port ASin2 **566** and will instead propagate its energy to port ASout1a **562**. It should be understood that the device **550** is otherwise functionally and operationally identical to the device **500** and descriptions and comments relating to the device **500** are applicable to device **550**.

Beside the use of a dichroic filter, it is important to note that other schemes can achieve the same function. For example, alternatively (not shown), a polarization dependent beam splitter or coupler can be used to couple the pulsed light λ_2 **572**. In such a configuration, light pulses of different polarizations are utilized. Light at λ_1 **518** can be in a polarization orthogonal to that of pulsed light λ_2 **572** so that the polarization dependent beam splitter or coupler will couple most of the pulsed light λ_2 **572** entering the port ASin2 **566** to Waveguide A **502** but not λ_1. In another alternative scheme (not shown), a mode-selective coupler is used to couple the pulsed light λ_2 **572**. In this scheme, pulsed light λ_2 **572** is coupled to a waveguide mode different from the propagating mode of light at λ_1 **518**. This can be achieved by using multimode waveguides for waveguide A such that light at λ_1 **518** is propagating in the lowest-order mode of waveguide A and pulsed light λ_2 **572** is coupled to the second-order mode of waveguide A. As is well known to those skilled in the art, the second order mode will have a larger angle of propagation (i.e. will be closer to the critical angle of escape) and can be designed to have a larger coupling coefficient than the lowest order mode. As a result, the mode selective coupler will couple most of the pulsed light λ_2 **572** entering the port ASin2 **566** to Waveguide A **502** but will not couple much of λ_1 from waveguide A to port ASin2 **566**.

It should be understood that the energy exiting the port BPout1 **514** (as continuous wave (CW) light at λ_1 (CW PWR BYPASS OUT λ_1) **520**) can be designed to be substantially unaffected in this entire process. The energy exiting the port BPout1 **514** of the IGHL Phosistor **500, 550** of FIGS. 6A and 6B is cable of being reused to power another phosistor. This feature is analogous to the supply voltage in electronic logic and switching circuitry.

Specifically, there is a range of gain for the gain medium from zero up to a certain critical gain value for which the energy exiting the port BPout1 **514** (i.e. the energy of light at λ_1, CW PWR BYPASS OUT λ_1 **520**), is not substantially affected and the energy exiting the port ASout1 **511** gain substantially to approach the energy exiting the port BPout1 **514**. When the gain begins to exceed this critical value, the intensity of λ_1 **513** (SIG OUT λ_1) exiting port ASout1 **511** will begin to be substantially higher than the intensity of λ_1 **520** (CW PWR BYPASS λ_1) exiting port BPout1 **514**.

It should be understood that the speed of switching can be fast as the active medium **508** when in the gain state at λ_1 (Case B in FIG. 4B) will be driven back to the transparency state at λ_1 (Case C in FIG. 4C) rapidly by the light at λ_1 **518** passing through the gain medium **508** when pulsed light at λ_2 **522, 572** is removed. The state of the active medium **508** is again analogous to case C, as illustrated in FIG. 4C. In the longer time scale, the active medium will relax back to the state of loss analogous to Case A, as illustrated in FIG. 4C. As described below, it is some times desirable to keep the initial state of the active medium to be in the state of transparency, There are various ways to maintain the active medium to be initially in the state of transparency. One way is to provide a constant excitation to the active medium from the light at λ_2 **522**, or from any other constant intensity light at λ_2. Thus the light λ_2 **522** can be a pulsed light source above a constant background intensity. Another way is to provide a constant excitation current to the active medium through a PN or PIN junction such as the active medium **450** illustrated in FIG. 5C. This constant excitation current will be biased at

the level required to make the medium transparent when there is no excitation light beam interacting with the medium.

ii).   General Operation of the Device

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An exemplary operation of the device can be illustrated via the results of computer simulations as shown in FIGS. 6C-1, 6C-2, 6C-3, and 6C-4 for operation at 1500nm wavelength range. For this simulation, the active medium **420** is assumed to have a full-excitation gain coefficient of about 1

10   per μm, and ℓ_c is 15 μm. FIGS. 6C-1, 6C-2, and 6C-3 show the spatial distribution of the electric field strength for the light input at λ_1 **518** after propagating into waveguides A and B. The upper parts of FIGS. 6C-1, 6C-2, 6-C3 are 2-D plots for which the brightness shows the relative field strength, and the lower parts of FIGS. 6C-1, 6C-2, 6C-3 are 3-D plots for which the

15   heights show the relative field strength. FIG 6C-4 shows the relative powers at the output ports of waveguide A (port ASout1) and waveguide B (BPout1) as a function of -gL (negative of the product between the gain coefficient g and the medium length L). In the figure, the output at ASout1 is shown as dashed line, the output at BPout1 is shown as dotted line, and the solid line is

20   the sum of the outputs at ASout1 and Bpout1 (i.e. the dashed line plus the dotted line).

FIG. 6C-1 shows the situation when the gain medium is in the state of loss or transparency (at a gain coefficient of 0 per μm or gL=0). From FIG. 6C-1, it is evident that most of the energy of λ_1 **518** exits from the Waveguide

25   B **504** at the port BPout1 **514**. FIG. 6C-2 shows the situation when the medium is excited to the critical gain value (at a gain coefficient of about 0.4 per μm or a gL=3.0) by the pulsed light λ_2 **572**. From FIG. 6C-2 it is evident that approximately an equal amount of energy of λ_1 exits from Waveguide A and Waveguide B and the energy exiting waveguide B is not substantially

30   affected (it increased by at most a factor of two). FIG. 6C-3 shows the situation when the medium is excited above the critical gain value (at a gain

coefficient of about 1 per μm or a gL=7.5) for which the energy exiting waveguides A and B are increased substantially from their values of FIG. 6C-1. From figure 6C-4, we see that a good operating point is at just above the critical value for which the energy exiting waveguide A is much more than the energy exiting waveguide B, which means the gain medium is transferring most of its energy to output ASout1 at waveguide A, thereby achieving high energy conversion efficiency.

· We note that FIG. 6C-1 and FIG. 6C-2 in particular, show the two representative interference flux patterns of light for the device, which is dependent on the state of the active medium. One can switch between these two representative interference flux patterns of light by changing the state of the active medium through the action of another light beam.

iii).   Comments

We note that choosing an interaction length ℓ not equal to ℓ_c will result in some light energy at λ_1 propagating to port ASout1 **511** even when the medium is in a state of transparency and hence less light energy at λ_1 transferring to port BPout1 **514**. In this case, when the medium goes to the state of gain, additional light energy at λ_1 will still be channeled to port ASout1 **511** along waveguide A. Hence, other than the initial leakage of light energy at λ_1 to port ASout1 **511**, the general operation of the device remains unchanged from the case where $\ell = \ell_c$. This initial leakage of light may be useful in photonic circuits based on non-return-to-zero pulse operation for which it is desired that light energy not be returned to the zero value even at the low signal state.

It should be understood that in the typical operation of Phosistors, including the useful embodiments **500, 550**, one or more light inputs or outputs are described as continuous wave (CW) light. The light can otherwise be a pulsed light in some specific applications. For the purpose of illustration and not limitation it is taken as CW light.

The pulsed light at λ_2 **522** entering the port ASin2 **516** will excite the active medium **508**, providing gain at the operating wavelength λ_1 to the active medium **508** located in Waveguide A **502**.

It should be understood that the pulsed light at λ_2 **522, 572** can be input to the active medium **508** on Waveguide A **502** in any manner of implementation, in addition to using the input structures **506** and **556** described in FIGS. 6A and 6B. For example, it can impinge on the active medium from outside the waveguides (e.g. from the top at a direction perpendicular to waveguide A).

Since the active medium **508** of devices **500, 550** of FIGS. 6A and 6B is operated in the gain mode, this phosistor has a "gain gate". This gate is in the input arm (Waveguide A **502**).

If the medium is originally in the state of transparency, then the number of electrons excited in the active medium **508** would be approximately equal to the number of photons from the pulsed light at λ_2 absorbed by the medium **508**. Likewise, the number of photons generated at λ_1 and propagated toward the output port(s) of Waveguide A **502** would be approximately equal to the number of electrons excited, if the photons are generated at λ_1 before the free decay of the electrons which takes place at nanosecond time scale (for semiconductor medium). As a result, the number of photons out at λ_1 would be close to (i.e. correlated to) the number of photons in at λ_2 if the medium **508** fully absorbed the photons at λ_2. This is called quantum-number correlation. When this happens, the devices **500, 550** can be used as high or near unity quantum efficiency devices. The net action of the exemplary devices **500, 550** is to translate a beam of photons to a longer wavelength. Hence, this device can act as a quantum-number correlated wavelength up shifter, for example. Further, this device is non-reversible in that a pulse light of wavelength at λ_1 propagated backward into the output port ASout1b **524** will not generate a pulsed light at λ_2 **522** exiting the port ASin2 **516**. Hence, this device may act as an optical diode.

iv). MMI Configuration Device

As mentioned above, this device may be implemented in the form of a
multimode interference (MMI) configuration device, device **M500**, as shown in
FIG. 6D, which preferably includes a multimode interference (MMI)
Waveguide MMI **M5024**, in place of the directional coupler formed by
waveguide A and B. The multimode interference MMI Waveguide **M5024**
preferably includes a first arm or pathway (along the line joining A and A' in
the Figure) in place of waveguide A and a second arm or pathway (along the
line joining B and B' in the figure) in place of waveguide B. The MMI
Waveguide **M5024** preferably includes an active medium, which is illustrated
as a shaded region **M508** in FIG 6D along its first arm. It should be
understood that the device **M500** is otherwise functionally and operationally
identical to the device **500** and descriptions and comments relating to the
device **500** are applicable to device **M500** (except with Figure labels now
carrying prefix M). The exemplary specific physical dimensions are given
below. The similarity between the operation of the MMI device and the
coupler device may be illustrated by the field pattern shown in FIG. 6E-1,
which describe the same situation as FIGS. 6C-1 and the field pattern shown
in FIG. 6E-2, which describe the same situation as FIGS. 6C-2. In the case of
FIG. 6E simulation, the preferred and exemplary device dimensions (as
indicated in FIG. 6D) are chosen as follows: ℓ is taken to be 4.3 Microns, W is
1.2 microns, Wg is 0.405 microns, and L is 2.15 microns.

v). Resonator Configuration Device

As mentioned above, this device may be implemented in the form of a
resonator configuration device, device **R500**, as shown in FIG. 6F-1, which
preferably includes waveguide A **R502** coupled to a short waveguide B' **R515**,
which is part of an optical resonator **R517** formed by a closed-loop
waveguide. These waveguides are the same as waveguide A in that they are

preferably made up of high refractive index materials to enable waveguiding. The closed loop resonator **R517** is coupled also to another waveguide B **R504**. The coupling of light energy between the resonator and waveguide A and waveguide B can be achieved, for example, through a gap filled with lower refractive index materials (lower than the refractive index of the waveguide) as indicated by the gap separation Wg1 and Wg2 in the FIG. 6F-1. The resonator can be in the form of a ring having a certain waveguide core thickness t (see figure 6F-5), disk having a certain waveguide core thickness t (see figure 6F-6), or sphere having a certain diameter d (see figure 6F-7), or other geometrical deformation from that of a ring, disk, or sphere as long as the optical resonance effect is achieved. As is well known to those skilled in the art, the waveguide and resonator that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner (see figure 6F-6 illustrated for the exemplary case of a disk) but can be placed in a top-down vertical manner (see Figure 6F-8 illustrated for the exemplary case of a disk) or any other manners with respect to the horizontal substrate. Note that the coupling can also be achieved with the use of MMI couplers for which no gap is needed and the coupling region is also filled with high refractive index materials.

Waveguide A **R502** and resonator-waveguide B'-R-B (**R515**, **R517**, **R504**) are used in place of the directional coupler formed by waveguides A and B. The amount of light energy coupling from waveguide A to waveguide B' can be low, preferably in the range of a few percentage points (e.g. 5% achievable with an interaction length ℓ of 1.5 to 2 microns for a 0.4 micron gap between waveguides A and B'). As is well known to those skilled in the art, at the resonant frequency the closed-loop resonator allows energy to build up to an intensity level that is much higher than the input light intensity in waveguide A (e.g. 20 times higher). Preferably, part of the light energy (e.g. 5%) in the resonator loop will exit back to waveguide A with a phase opposite from (and an intensity equal to) that of the light originally in waveguide A, thereby canceling the light energy in waveguide A after the coupling region (i.e. the region spanned by waveguide B'). Preferably, part of the light energy

(e.g. 5%) in the resonator loop will exit to waveguide B **R504**, the net result of which is an effective total transfer of light energy from waveguide A **R502** to waveguide B **R504** through the closed-loop resonator. A clear advantage of the resonator configuration device is the shorter coupling length needed to

5   achieve the same effect (in this case shorter by a factor of 10 for 5% coupling). A disadvantage is the narrow wavelength operating range, which requires the operating wavelength to be at or around the resonance frequency of the resonator.

The Waveguide A **R502** preferably includes an active medium **R508**

10   preferably just after the intersection point of waveguide A with the resonator, which is illustrated as a gray region in FIG 6F-1. It should be understood that the device **R500** is otherwise generally functionally and operationally identical to the device **500** and descriptions and comments relating to the device 500 are generally applicable to device **R500** (except with figure labels now

15   carrying prefix R).

The resonator can also be in other form such as multiple closed-loop resonators as shown by device **RM500** in FIG. 6F-2, which shows an example of three closed-loop resonators **RM517, RM519, RM521,** made up of high refractive index materials similar to those used in waveguide A. The resonator

20   can be in the form of a disk (**RD517, RD519**) or a box (**RD521**) or spherical (not shown) shaped resonators as shown by device **RD500** in FIG. 6F-3. For these resonators, preferably the center parts of the closed-loops are solid and either whispering-gallery modes or modes formed by repeated reflection from the resonator side walls are utilized to achieve optical resonances. The

25   coupling to the resonators can be through a gap of low refractive index or a small joint in the form of an MMI coupler as illustrated by device **RMG500** in FIG. 6F-4. In this device RMG500, three of the coupling regions (Wc1, Wc2 and Wc4) are such MMI couplers. It should be understood that the devices **RM500, RD500, RMG500** are otherwise generally functionally and

30   operationally identical to the device **500** and descriptions and comments relating to the device **500** are generally applicable to the devices **RM500,**

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RD500, and **RMG500** (except with Figure labels now carrying prefixes RM, RD, and RMG, respectively).

vi).   PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

As mentioned above, the optical waveguide in either the directional coupler configuration or the MMI configuration or the resonator configuration may be implemented in the form of a photonic bandgap (PBG) structure. For the case of the directional coupler configuration, the PBG structure is shown by exemplary device **PC500** in FIG. 6G-1. The photonic-bandgap structure preferably includes a photonic bandgap waveguide A **PC502** and a photonic bandgap waveguide B **PC504**. The photonic bandgap PBG Waveguide A or B preferably includes a series of periodically placed holes defined within low-refractive index materials outside the waveguiding region and high-refractive index materials within the waveguiding region of the structure. As is known to those skilled in the art, these series of holes form a forbidden wavelength gap for the propagation of electromagnetic field, resulting in light confining in the region identified as the photonic bandgap structure. For example, for a refractive index contrast of n=3.8 (Black region) to n=1 (white region), the vertical distance between center of the hole to center of the hole can be 0.527 microns, the horizontal distance between the center of the hole to center of the hole can be 0.608 microns, the diameter of the holes can be 0.4 microns, which will provide a photonic bandgap at about a 1.5 μm **(or 1500nm)** wavelength. The interaction length ℓ is chosen to achieve maximal energy coupling. The photonic bandgap waveguide A **PC502** preferably includes an active medium, which is illustrated as a shaded region **PC508** in FIG. 6G-1. Photonic bandgap waveguide A **PC502** or waveguide B **PC504** in device **PC500** functions as waveguide A **502** or waveguide B **504** in device **500**. It should be understood that the device **PC500** is otherwise functionally and operationally identical to the device **500** and descriptions and comments

relating to the device **500** are generally applicable to device **PC500** (except with figure labels now carrying prefix PC).

Similarly, the MMI configuration may be implemented in the form of a photonic bandgap structure as shown by device **PM500** in FIG. 6G-2. It should be understood that the device **PM500** is otherwise generally functionally and operationally identical to the device **M500** and descriptions and comments relating to the device **M500** are applicable to device **PM500**. Likewise, the resonator configuration may be implemented in the form of a photonic bandgap structure as shown by device **PRD500** in FIG. 6G-3. As is well known to those skilled in the art, resonators can be formed with photonic-bandgap structures by removing a single hole (as is the case for FIG. 6G-3) or groups of holes (not shown). It should be understood that the device **PRD500** is otherwise functionally and operationally identical to the device **RD500** and descriptions and comments relating to the device **RD500** are applicable to device **PRD500** (except with figure labels now carrying prefix PRD).

It should be understood that the dimensions and materials for the devices are presented for purposes of illustrating useful embodiments of the devices **M500, R500, RM500, RD500, RMG500, PC500, PM500, PRD500** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **M500, R500, RM500, RD500, RMG500, PC500, PM500, PRD500.** A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety of materials can be used, for example, the waveguides do not have to be semiconductor and may be optical fibers, glass, or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved). Furthermore, the active medium does not have to be a semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite gain/loss/transparency properties are achieved), and the resonators do not have to be semiconductor material but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the shape of the Waveguides, MMI Structures, Photonic Bandgap Structures,

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or Resonators do not generally have to be linear, circular, parallel, or regular in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

Finally, it should be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the refractive index of the active medium could occur when the active medium changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the implementations of these devices include situations whereby both the gain/transparency/loss property as well as the refractive-index property of the active medium are used during operation of the devices.

B.   EXEMPLARY DEVICE 2

FIG. 7 illustrates a second general embodiment **600** of a phosistor device employing directionally coupled waveguides. The device can perform as a switching element and can in particular switch or convert a stream of slow or ultra fast (picosecond, femtosecond) optical pulses at low energy and long wavelength to a stream of slow or ultrafast optical pulses at comparatively high energy (and comparatively short wavelength). The device **600** is not limited to use as a switching element and can be utilized, for example, as an all-optical logic gate, a light intensity amplifier, a photon duplicator, a light intensity modulator, a light intensity regulator, an optical phase shifter, a lossless signal tap, an optical detector, and a variable optical attenuator. It should be understood that these exemplary applications of device **600** are intended to illustrate the wide range of uses for device **600**, and are not intended to limit the applications of other exemplary embodiments of device **600** to these examples. The device can be referred to as an

"Output-Arm-Loss-Gate Low-to-High-Energy Inversion Phosistor" (OLLH Phosistor **600**).

OLLH Phosistor **600** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **602** and a second pathway of light consisting of the spatial region occupied by Waveguide B **604**. The Waveguide B **604** preferably includes an active medium **608**. As described above, Waveguide B **604** can be implemented as waveguide **430** with active medium **420** and Waveguide A **602** can be implemented as waveguide **400** in a useful embodiment. The Waveguide A **602** preferably includes an input port APin2 **610** and an output port ASout2 **612**. The Waveguide B **604** preferably includes an input port BSin1 **606** and an output port BPout2 **614** which doubles as a possible input port (not shown in FIG. 7). FIG. 7 shows that Waveguide A **602** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **604**, which has width W_B, so that a wave in Waveguide A can be coupled to a wave in Waveguide B. The terms "wave" and "light beam" are used interchangeably.

For the input port labeled "APin2" (**610**), "P" stands for Power-Supply beam, "A" refers to Waveguide A **602**, "in" refers to **610** being an input port, and "2" refers to the input wavelength being λ_2. For the output port labeled "ASout2" (**612**), "S" stands for Signal beam, "A" refers to Waveguide A **602**, "out" refers to it being an input port, "2" refers to the input wavelength being λ_2. For the input port labeled "BSin1" (**606**), "S" stands for Signal beam, "B" refers to Waveguide B **604**, "in" refers to **606** being an input port, and "1" refers to the input wavelength being λ_1. For the output port labeled "BPout2" (**614**), "P" stands for Power-Supply beam, "B" refers to Waveguide B **604**, "out" refers to it being an output port, and "2" refers to the output wavelength being λ_2.

The input port APin2 **610** on the waveguide A is configured to receive continuous wave (CW) light **618** having wavelength λ_2 (at λ_2) (CW PWR IN λ_2). Under certain conditions described below when the active medium on the

waveguide reaches transparency and Waveguides A and B are optically transparent, most of the CW light at λ_2 **618** propagating along the Waveguide A **602** will be transferred to Waveguide B **604** after a coupling length ℓ_c. The CW light at λ_2 **618** then exits from Waveguide B **604** at the port BPout2 **614** as light at λ_2 (NEG SIG OUT λ_2) **620**.

The coupling length is defined as the length at which a wave in one waveguide maximally couples into another waveguide that is coupled to the first waveguide. In this device **600**, the interaction length ℓ, defined as the length of interaction between Waveguides A **602** and B **604**, is equal to the full coupling length ℓ_c so that $\ell = \ell_c$.

As shown in FIG. 7, the length L of the active medium **608** is about the interaction length ℓ ($L \cong \ell$). The length L of the active medium **608** may be somewhat longer or shorter than ℓ. Varying the length L of the active medium **608** relative to the interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **600** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **600**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

For example, while the choice of $\ell = \ell_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ_c (or multiple odd numbers of ℓ_c) without affecting the general operating principle of the device.

Also, it should be understood that the shape of the waveguides do not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an

alteranative location along waveguide B other than that illustrated in FIG 7, and there can be more than one disconnected active medium areas along waveguide B. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal

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manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel or have the same widths and dimensions as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of device **600**, for operation at 800nm

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wavelength range, the wavelength λ_1 can be at 820nm, λ_2 can be at 800nm, and the Waveguide A **602** can be implemented as the Waveguide 400 illustrated in FIG. 5A and Waveguide B **604** can be implemented as Waveguide **430** with an active medium **420** illustrated in FIGS. 5B and 5C, in an $Al_xGa_{1-x}As$ embodiment for the waveguide core having alloy composition x

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at 0.3 giving a bandgap energy of around 690nm. Thus the core material is transparent at the wavelength λ_2 of 800nm. When the active medium is fully de-excited, the active medium absorbs light at both 800nm and 820nm wavelengths. The active medium is an essentially three-level medium described in FIG. 4A-D for which electrons are free to relax from the upper-

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energy level corresponding to the 800nm absorption to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of devices 600, for operation at 1500nm wavelength range, the wavelength λ_1 can be at 1500nm, λ_2 can be at 1480nm, and the Waveguide A **602** can be implemented as the Waveguide **400**

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previously illustrated in FIG. 5A and Waveguide B **604** can be implemented as the Waveguide **430** with an active medium **420** illustrated in FIGS. 5B and 5C, in an $In_{1-x}Ga_xAs_{1-y}P_y$ embodiment for the waveguide core having alloy compositions x=0.16 and y=0.67 giving a bandgap energy of around 1100 nm. Thus the core material is transparent at the wavelength λ_1 of 1480nm. When

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the active medium is fully de-excited, the active medium absorbs light at both 1480nm and 1500nm wavelengths. The active medium is an essentially three-

level medium described previously in FIG. 4A-D for which electrons are free to relax from the upper-energy level corresponding to the 1480nm absorption to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for operation at the 1500nm wavelength range, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. FIG. 7 illustrates that Waveguide A **602** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **604**, which has width W_B. In this exemplary embodiment, the Waveguide A **602** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_g from Waveguide B **604** of 0.4 μm, while Waveguide B **604** has width W_B equal to 0.4 μm. In this exemplary embodiment, ℓ_c and ℓ are each 15 μm.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **600** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **600**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i).   **Exemplary Device Operations**

There are various modes for which this device may function. Below, we will describe three exemplary and useful operating modes of the device.

First Exemplary Operating Mode

In the first exemplary and useful operating mode of the device, continuous wave (CW) light having wavelength λ_2 (at λ_2) (CW PWR IN λ_2) **618** enters at the port APin2 **610** on the Waveguide A **602**. In the initial state, the active medium **608** along Waveguide B **604** is not excited and is in the state of loss analogous to Case A, as illustrated in FIG 4A. The CW light at λ_2 **618** propagates along the Waveguide A **602** and some of its energy is leaked

to Waveguide B **604** through evanescent coupling. As the portion of CW light at λ_2 **618** reaches the active medium **608** on Waveguide B, it drives the active medium **608** to a state of transparency at λ_2. The intensity of λ_2 must be high enough so that $I_2 > (1 / \eta) I_{2Sat}$. That is, the intensity of the light at λ_2 must exceed the saturation intensity divided by η, the effective percentage of leakage power to the Waveguide B **604** needed to bring the active medium in waveguide B to the state of transparency when there is no pulsed light at λ_1 **622** entering the port BSin1 **606** (i.e., an input off state). This state of the active medium **608** is analogous to Case D, as illustrated in FIG. 4D.

The input port BSin1 **606** on Waveguide B **604** is the input signal port for pulsed light having wavelength λ_1 (SIGNAL IN λ_1) **622**. The pulsed light λ_1 **622** entering the port BSin1 **606** will de-excite or relax the active medium **608**, providing loss at the operating wavelength λ_2 to the active medium **608** located in Waveguide B **604**. This state of the active medium **608** is analogous to Case C, as illustrated in FIG. 4C. The CW light at λ_2 **618** from input port APin2 **610** loses energy in the active medium **608**, so that most of the CW light at λ_2 **618** does not transfer to Waveguide B **604** and thus does not exit from the output on BPout2 **614**. Rather, most of the CW light at λ_2 **618** propagates through Waveguide A **602** and exits out of the output port ASout2 **612** as a pulse of light at λ_2 (SIGNAL OUT λ_2) **628** out of the first Waveguide A **602** and its energy exiting port BPout2 **614** is substantially reduced when a pulse of light at λ_1 **622** is present.

When pulsed light at λ_1 **622** is removed, the active medium will be driven back to the transparency state at λ_2 (Case D in FIG. 4D) by the light at λ_2 **618** passing through the loss or absorbing medium **608**, and most of CW light at λ_2 **618** will transfer to Waveguide B **604** and thus will again exit from the output on BPout2 **614**. The net effect in this first exemplary and useful operating mode of the device of FIG. 7 is that in the initial state, most of the CW light at λ_2 **618** from input port APin2 **610** couples to Waveguide B **604**

and exits out of output port BPout2 **614** as CW λ_2 **620**. The pulsed light at λ_1 **622** into port BSin1 **606** generates a positively going pulse of light (light with an increased intensity during the pulse duration) at λ_2 **628** exiting port ASout2 **612** and a negatively going pulse of light (light with a reduced intensity during the pulse duration) **at** λ_2 **620** exiting port BPout2 **614.** Upon cessation of the pulsed light at λ_1 **622,** the light at λ_2 **628** returns to its initial state and most of the light at λ_2 **628** exits out of output port BPout2 **614** as CW λ_2 **620**.

Second Exemplary Operating Mode

In the second exemplary and useful operating mode of the device, the intensity of λ_2 **618** is lower than the intensity required to driving the active medium to the state of transparency at λ_2. In this case the CW light at λ_2 **618** will not be able to drive the medium back to transparency by itself after pulsed light at λ_1 **622** is removed. A separate third input light beam with a wavelength λ_{tr} equal to or short than λ_2 is introduced to drive the active medium back to transparency. This third light beam λ_{tr} **624** can be input through port BPout2 **614** propagating towards the active medium **608.** The intensity of this third light beam I_{tr} should be high enough to bring the active medium to a state of transparency upon the removal of pulsed light at λ_1 **622**. The third light beam λ_{tr} **624** can be present in a pulsed manner such as after (or in alternation with) the input light beam λ_1 **622** or can be present as a CW beam. In the case where both light beams λ_{tr} **624** and λ_1 **622** are concurrently present, it is desirable that the intensity I_{tr} of light beam λ_{tr} **624** not be so high as to prevent light beam λ_1 **622** from de-exciting the active medium. The net effect in this second exemplary and useful operating mode of the device of FIG. 7 is that in the initial state, most of the CW light at λ_2 **618** from input port APin2 **610** couples to Waveguide B **604** and exits out of output port BPout2 **614** as CW λ_2 **620**. The pulsed light at λ_1 **622** into port BSin1 **606** generates

a positively going pulse of light (light with an increased intensity during the pulse duration) at λ_2 **628** exiting port ASout2 **612** and a negatively going pulse of light (light with a reduced intensity during the pulse duration) at λ_2 **620** exiting port BPout2 **614**. In the case where light beam λ_{1r} **624** is present in a CW manner, upon cessation of the pulsed light at λ_1 **622**, the light at λ_2 **628** returns to its initial state and most of the light at λ_2 **628** exits out of output port BPout2 **614** as CW λ_2 **620**. In the case where light beam λ_{1r} **624** is present in a pulsed manner, upon cessation of the pulsed light at λ_1 **622** and after a pulse of light beam λ_{1r} **624** is introduced, the light at λ_2 **628** returns to its initial state and most of the light at λ_2 **628** exits out of output port BPout2 **614** as CW λ_2 **620**.

In order for light beams λ_1 **622** or λ_{1r} **624** to interact with the active medium effectively, it may be desirable that they do not couple much of their energy from waveguide B to waveguide A, though such coupling will not affect the general operating principle of the device. This can be achieved for example by placing light beams λ_1 **622** or λ_{1r} **624** in a polarization different from that of light beam λ_2 **618,** and by having weak or negligible coupling between waveguides A and B for light beams λ_1 **622** or λ_{1r} **624** but strong coupling for light beam λ_2 **618.** That is by having waveguides A and B to be a polarization dependent coupler. Alternatively, the can be achieved by having waveguides A and B to be a mode selective coupler and by having light beams λ_1 **622** or λ_{1r} **624** to be in a different propagating waveguide modes (e.g. to be in the first order propagating mode) from that of light beam λ_2 **618** (e.g. to be in the second order propagating mode).

Third Exemplary Operating Mode

In the third exemplary and useful operating mode of the device, the intensity of λ_2 **618** is lower than the intensity required to drive the active

medium to the state of transparency at λ_2. In this case the CW light at λ_2 **618** will not be able to drive the medium back to transparency by itself after pulsed light at λ_1 **622** is removed. In this case an active medium with a PN or PIN junction, such as active medium **425** illustrated in 5D, is used in place of active medium **420** along waveguide B. A constant forward bias voltage and current is applied to medium **425** to drive the active medium back to transparency. This forward bias current should be high enough to bring the active medium to a state of transparency upon the removal of pulsed light at λ_1 **622.** However, it is desirable that this forward bias current not be so high as to prevent light beam λ_1 **622** from de-exciting the active medium. The state of the active medium is in the state of transparency analogous to Case C, as illustrated in FIG. 4C. The net effect in this third exemplary and useful operating mode of the device of FIG. 7 is that in the initial state, most of the CW light at λ_2 **618** from input port APin2 **610** couples to Waveguide B **604** and exits out of output port BPout2 **614** as CW λ_2 **620.** The pulsed light at λ_1 **622** into port BSin1 **606** generates a positively going pulse of light (light with an increased intensity during the pulse duration) at λ_2 **628** exiting port ASout2 **612** and a negatively going pulse of light (light with a reduced intensity during the pulse duration) at λ_2 **620** exiting port BPout2 **614.** Upon cessation of the pulsed light at λ_1 **622,** the light at λ_2 **628** returns to its initial state and most of it exits out of output port BPout2 **614** as CW λ_2 **620.**

ii). General Operation of the Device

An exemplary operation of the device can be illustrated via the result of computer simulation as shown in FIGs. 7A-1, 7A-2, and 7A-3 for operation at the 1500nm wavelength range. FIGs. 7A-1 and 7A-2 show the spatial distribution of the electric field strength for the light input at λ_2 **618** after propagating into waveguides A and B. The upper parts of FIGs. 7A-1 and 7A-2 are 2-D plots for which the brightness shows the relative field strength, and

the lower parts of FIGs. 7A-1 and 7A-2 are 3-D plots for which the heights show the relative field strength. FIG 7A-3 shows the relative power at the output ports of waveguide A (port ASout2 **612**) and waveguide B (port BPout2 **614**) as a function of −gL (the product of the loss coefficient −g and the medium length L). In the figure, the output at ASout2 is shown as dotted line, the output at BPout2 is shown as dashed line, and the solid line is the sum of the outputs at ASout2 and BPout2 (i.e. the dashed line plus the dotted line). FIG. 7A-1 shows the situation when the gain medium is in the state of transparency (at a loss coefficient of 0 per μm or −gL=0). From FIG. 7A-1, it is evident that most of the energy of λ_2 **618** exits from Waveguide B **604** at the port BPout2 **614**. FIG. 7A-2 shows the situation when the medium is de-excited to the state of loss at λ_2 by the pulsed light at λ_1 **622** (at a gain coefficient of about -3.3 per μm or −gL=50). From FIG. 7A-2, it is evident that most of the energy of λ_2 exits from Waveguide A. FIG. 7A-1 and FIG. 7A-2 show the two representative interference flux patterns of light for the device, which is dependent on the state of the active medium. In particular, one can switch between these two representative interference flux patterns of light by changing the state of the active medium through the action of another light beam. Note that beside these two states, there are other states, for example the intermediate state at −gL=6 shown in FIG. 7A-3, for which there is substantial total energy absorbed by the loss medium so that both output ports at waveguide A and waveguide B have low output power.

iii).   Comments

In should be understood that in the typical operation of Phosistors, including the useful embodiment **600**, one or more light inputs or outputs are described as continuous wave (CW) light. The light can otherwise be a pulsed light in some specific applications. For the purpose of illustration and not limitation it is taken as CW light.

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The phosistor device **600** is capable of providing photon gain under certain operating condition. This is due to the fact that a light pulse at λ_1 can create an output pulse having an increased number of photons. This increase can be quite significant.

It should be understood that the speed of switching can be fast as the active medium **608**, when in the loss state at λ_2 (Case C in FIG. 4C), will be driven back to the transparency state at λ_2 (Case D in FIG. 4D) rapidly by the light at λ_2 **618** passing through the loss or absorbing medium **608** when pulsed light at λ_1 **622** is removed. The state of the active medium **608** is again analogous to Case D, as illustrated in FIG. 4D.

It should be understood that the pulsed light at λ_1 **622** can be input to the active medium **608** on Waveguide B **604** in any manner of implementation. In particular, the pulsed light at λ_1 **622** can enter either input port BSin1 **606** or output port BPout2 **614** which doubles as a possible input port (not shown in FIG. 7). It can also impinge on the active medium from outside the waveguides (e.g. from the top at a direction perpendicular to waveguide B). The problem of any mixing of light that might occur can be addressed with use of a dichroic filter/coupler or polarization-selective coupler or mode-selective coupler (not shown).

Since the active medium **608** of device **600** of FIG. 7 is operated at the absorbing or loss mode, this phosistor has a "loss gate". This gate is in the output arm (Waveguide B **604**).

iv). Exemplary Device 2 as a Wavelength Multiplexer/De-Multiplexer or Wavelength Selective Switch

In another useful embodiment of device 2, the waveguide A and B have unequal widths W_A and W_B. As is well known to those skilled in the art, waveguide couplers with unequal waveguide widths will have strong wavelength sensitivity. In particular, when the active medium is in the transparency state, only certain wavelength of light will couple maximally from

waveguide A to waveguide B, thus allowing the device to act not only as a switch but as a wavelength selective switch. Except the difference in the waveguide widths providing wavelength sensitivity, this embodiment of the device is otherwise functionally and operationally identical to the device **600**
5   and descriptions and comments relating to the device **600** are generally applicable to this device.

v).   Multiple Waveguide Version of Device 2

10   As a variation of geometry, device 2 can be realized in the form of a multiple-waveguide device such as a three-waveguide structure. This device, device **CB600**, is shown in FIG. 7AA, where light beam in Waveguide A is first coupled to light beam in Waveguide G, which contains the active medium. Light beam in Waveguide G is then coupled to light beam in waveguide B.
15   The waveguide widths of Waveguides A, B, and G can be identical or different from each others, as long as the required couplings of light beams are achieved. The input port for SIGNAL IN λ_1 (BSin1) is preferably connected to waveguide G so that the input pulse at λ_1 can reach the active medium as before. The interaction length ℓ is chosen so that when the medium is in the
20   state of transparency, preferably most of the energy in waveguide A will be coupled to waveguide B (through waveguide G). Let us denote this length as $\ell = \ell_c'$. It should be understood that the device **CB600** is otherwise functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are applicable to device **CB600** (except
25   with figure labels now carrying prefix CB). This three-waveguide structure can be generalized to more than three waveguides by inserting more parallel coupled waveguides between waveguide A and B.

This version of device 2 has an advantage in that the active medium is now on waveguide G, which makes it easier to introduce pulsed light at λ_1 to
30   interact with the active medium. Furthermore, this is a symmetric structure so that port BPin2 functions like port APin2 and port BPout2 functions like port

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ASout2. Hence, when the medium is in the state of transparency, light at λ_2 input to port APin2 will exit port BPout2 and light at λ_2 input into port BPin2 will exit port ASout2 (this is referred to as a Cross state). When the medium is in the state of loss, light at λ_2 input to port APin2 will stay in waveguide A and exit port BSout2 and light at λ_2 input into port BPin2 will stay in waveguide B and exit port BPout2 (this is referred to as a Bar state). Such property allows one to realize a Cross-Bar Switch or a 2x2 optical switch. As is well known to those skilled in the art, a 2x2 optical switch can be cascaded to implement an NxM optical switch.

vi).   MMI Configuration Device

As mentioned above, this device may be implemented in the form of a multimode interference (MMI) configuration device, device **M600**, as shown in FIG. 7B, which preferably includes a multimode interference (MMI) Waveguide **M6024**, in place of the directional coupler formed by waveguide A and B. The multimode interference MMI Waveguide **M6024** preferably includes a first arm or pathway (along the line joining A and A' in the figure) in place of waveguide A and a second arm or pathway (along the line joining B and B' in the figure) in place of waveguide B. The MMI Waveguide **M5024** preferably includes an active medium **M608**, which is illustrated as a gray region in FIG 7B along its first arm. It should be understood that the device **M600** is otherwise functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are applicable to device **M600** (except with figure labels now carrying prefix M). The exemplary specific physical dimensions are given below. The similarity between the operation of the MMI device and the coupler device may be illustrated by the field pattern shown in FIG. 7C-1, which describes a similar situation as FIG. 7A-1 and the field pattern shown in FIG. 7C-2, which describes a similar situation as FIG. 7A-2. In the case of FIG. 7C simulation, the device

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dimensions (as indicated in FIG. 7B) are chosen as follows: ℓ is taken to be 4.3 Microns, W is 1.2 microns, Wg is 0.405 microns, and L is 2.15 microns.

vii).   Resonator Configuration I Device

As mentioned above, this device may be implemented in the form of a resonator configuration device. There are two such configurations. An example for configuration I is device **R600** shown in FIG. 7D-1, which preferably includes waveguide A **R602** coupled to a short waveguide B' **R615**, which is part of an optical resonator **R617** formed by a closed-loop waveguide. These waveguides are the same as waveguide A in that they are made up of high refractive index materials. The closed loop resonator **R617** is coupled also to another waveguide B **R604**. The coupling of light energy between the resonator and waveguide A and waveguide B can be achieved, for example, through a gap filled with lower refractive index materials (lower than the refractive index of the waveguide) as indicated by the gap separation Wg1 and Wg2 in the figure. The resonator can be in the form of a ring (see figure 6F-5), disk (see figure 6F-6), or sphere (see figure 6F-7), or other geometrical deformation from that of a ring, disk, or sphere as long as the optical resonance effect is achieved. As is well known to those skilled in the art, the waveguide and resonator that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner (see figure 6F-6 illustrated for the exemplary case of a disk) but can be placed in a top-down vertical manner (see figure 6F-8 illustrated for the exemplary case of a disk) or any other manners with respect to the horizontal substrate. We not that the coupling can also be done with the use of MMI couplers for which no gap is needed and the coupling region is also filled with high refractive index materials.

Waveguide A **R602** and resonator-waveguide B'-R-B (**R615, R617, R604**) are used in place of the directional coupler formed by waveguides A and B. The amount of light energy coupling from waveguide A to waveguide B' can be low, preferably within the range of a few percentage points (e.g. 5%

achievable with an interaction length ℓ of 1.5 to 2 microns for a 0.4 micron gap between waveguides A and B'). As is well known to those skilled in the art, at the resonant frequency the closed-loop resonator allows energy to build up to an intensity level that is much higher than the input light intensity in

5   waveguide A (e.g. 20 times higher). Preferably, part of the light energy (e.g., 5%) in the resonator loop will exit back to waveguide A with a phase opposite from (and an intensity equal to) that of the light originally in waveguide A, thereby canceling the light energy in waveguide A after the coupling region (i.e. the region spanned by waveguide B'). Preferably, part of the light energy

10   (e.g. 5%) in the resonator loop will exit to waveguide B **R604**, the net result of which is an effective total transfer of light energy from waveguide A **R602** to waveguide B **R604** through the closed-loop resonator. A clear advantage of the resonator configuration device is the shorter coupling length needed to achieve the same effect (in this case shorter by a factor of 10 for 5%

15   coupling). A disadvantage is the narrow wavelength operating range, which requires the operating wavelength to be at or around the resonant frequency of the resonator.

The closed-loop resonator **R617** preferably includes an active medium. The active medium can be located either at the coupling point between

20   waveguide A and the resonator (Region I) **R608a** or located around any other parts of the resonator (e.g. Region II) **R608b**, or located at both regions I and II, including the case of having the active medium filling the entire resonator volume. Having the medium in region II will spoil the Q value of the resonator and prevent the field from building up in the resonator, and hence prevent the

25   coupling of substantial energy from waveguide A to waveguide B. Having the active medium in region I will cut off the coupling between waveguide A and the resonator when the active medium is in a loss state, which is in addition to spoiling the Q of the resonator, and hence will be more effective in preventing the coupling of substantial energy from waveguide A to waveguide B. Thus,

30   when the active medium is in the state of loss, the resonator is said to be in the OFF state for which light will remain in waveguide A. When the active medium is in the state of transparency, the resonator is said to be in the ON

state for which light will be transferred to waveguide B. A pulsed light at λ_1 will de-excite the active medium **R608**, providing loss at the operating wavelength λ_2 to the active medium **R608** located in the resonator **R604**. This pulse light can reach the active medium in a number of ways, including the use of a mode-selective coupler to couple light into the resonator with a separate waveguide from port BSin1 as shown in the figure. Other means of input is possible for the pulsed light at λ_1, including the use of polarization-selective coupler, dichroic filter/coupler, mode-selective coupler, or from outside the resonator via free-space propagation such as from the top of the resonator in a direction perpendicular to the plane of the resonator.

When the active medium is in a state of loss, the CW light at λ_2 **R618** from input port APin2 **R610** loses energy in the active medium **R608** (in this case through the action of a resonator) so that **most of** the CW light at λ_2 **R618** does not transfer to Waveguide **R604** and thus does not exit from the output on BPout2 **R614**. Rather, **most of** the CW light at λ_2 **R618** propagates through Waveguide A **R602** and exits out of output port ASout2 **R612** as a pulse of light at λ_2 (SIGNAL OUT λ_2) **R628** out of the first Waveguide A **R602** and its energy exiting port BPout2 R614 is substantially reduced when a pulse of light at λ_1 **R622** is present. In the case of FIG. 7D-1 the net effect is that the pulsed light at λ_1 **R622** into port BSin1 **R606** generates a pulse of light at λ_2 **R628** exiting port ASout2 **R612**.

Thus it should be understood that the device **R600** is otherwise functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are applicable to device **R600** (except with figure labels now carrying prefix R).

The resonator can also be in other form such as multiple closed-loop resonators as shown by device **RM600** in FIG. 7D-2, which shows an example of three closed-loop resonators **RM617, RM619, RM621** made up of high refractive index materials as waveguide A. The resonator can be in the form of disk (**RD617, RD619**) or box (**RD621**) or spherical (not shown) shaped

resonators as shown by device **RD600** in FIG. 7D-3. Preferably, for these resonators, the center parts of the closed-loops are solid and either whispering-gallery modes or modes formed by repeated reflection from the resonator side walls are utilized to achieve optical resonances. The coupling to the resonators can be through a gap of low refractive index or a small joint in the form of a MMI coupler as illustrated by device **RMG600** in FIG. 7D-4 for which three of the coupling regions (Wc1, Wc2 and Wc4) are such MMI couplers. It should be understood that the devices **RM600, RD600, RMG600** are otherwise functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are generally applicable to the devices **RM600, RD600,** and **RMG600** (except with figure labels now carrying prefixes RM, RD, and RMG, respectively).

viii).   Resonator Configuration II Device

Another implementation (configuration II) of a resonator configuration is shown by Device **RZ600** in FIG. 7E-1, which preferably includes waveguide C' coupled to a short waveguide B' that is part of an optical resonator **RZ617** formed by a closed-loop waveguide. The amount of coupling to waveguide B' can be low, preferably within the range of a few percentage points (e.g. 5%). As is well known to those skilled in the art, at the resonant frequency the closed-loop resonator allows energy to build up to an intensity level that is much higher than the input light intensity in waveguide C' (e.g. 40 times higher). Preferably, part of the light energy (e.g. 5%) in the resonator loop will exit back to waveguide C' with a phase opposite from and an intensity equal to that of the light originally in waveguide C', thereby resulting in shifting the phase of the light energy in waveguide C' by a Pi phase. By placing waveguide C' on one arm of an optical interferometer, this phase shift can be translated to an intensity switching. In FIG. 7E-1, the interferometer is formed by input waveguides A and B, a 50/50 beam splitter BS1, which splits light from input waveguide A to two arms of the interferometer C and C', another 50/50 beam splitter BS2, which combines light from C and C' and channel

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them to output waveguides A" and B". In some implementation, such as an ON/OFF type device or a 1X2 switch, one of the input waveguides (A and B) can be absent, or one of the output waveguides (A" and B") can be absent, or one of the input waveguides (A and B) and one of the output waveguides (A"

5   and B") can be both absent.

The resonator contains an active medium and can be in the On or OFF state as described in configuration I. When the resonator is in the OFF state (i.e. the medium is in the loss state), light at λ_2 entering waveguide A will exit waveguide A" due to constructive interference of the light at waveguide A"

10   after the combining beam splitter BS2 of the interferometer. When the resonator is in the ON state, an additional Pi phase shift in the C' arm of the interferometer will result in destructive interference of the light at waveguide A" but constructive interference of the light at waveguide B" and the light at λ_2 entering waveguide A will exit waveguide B". A pulsed light at λ_1 will de-excite

15   the active medium **RZ608** (i.e. **RZ608a** or **RZ608b** as described in the case of device **R600**), providing loss at the operating wavelength λ_2 to the active medium **RZ608** located in the resonator **RZ617**. This pulse light can reach the active medium in a number of ways, including the use of a polarization-selective coupler, dichroic filter/coupler, or mode-selective coupler to couple

20   light into the resonator with a separate waveguide from the input port **RZ622** as shown in FIG. 7E-1 or from outside the resonator via free-space propagation such as from the top of the resonator in a direction perpendicular to the plane of the resonator.

Light at λ_2 entering waveguide A and exiting waveguide A" after

25   propagating through waveguides C and C' forms a first interference flux pattern of light. Light at λ_2 entering waveguide A and exiting waveguide B" after propagating through waveguides C and C' forms a second interference flux pathway of light. When the active medium is in a state of loss, the CW light at λ_2 **RZ618** from input port APin2 **RZ610** loses energy in the active

30   medium **RZ608**, which alters the interference flux pattern of light (in this case through the action of a resonator) so that most of the CW light at λ_2 **RZ618**

does not transfer to Waveguide B" **RZ604** and thus does not exit from the output on BPout2 **RZ614**. Rather, most of the CW light at λ_2 **RZ618** propagates to Waveguide A" **RZ602** and exits out of output port ASout2 **RZ612** as a pulse of light at λ_2 (SIGNAL OUT λ_2) **RZ628** out of the first
5　　　Waveguide A" **RZ602** and its energy exiting port BPout2 RZ614 is substantially reduced when a pulse of light at λ_1 **RZ622** is present. In the case of FIG. 7E-1 the net effect is that the pulsed light at λ_1 **RZ622** into port BSin1 **RZ606** generates a pulse of light at λ_2 **RZ628** exiting port ASout2 **RZ612**.

　　　　　Thus it should be understood that the device **RZ600** is otherwise
10　　functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are generally applicable to device **RZ600** (except with figure labels now carrying prefix RZ).

　　　　　The resonator can also be in other form such as multiple resonators as shown by device **RZD600** in FIG. 7E-2, which shows an example of three
15　　resonators **RZD617, RZD619, RZD621** made up of high refractive index materials as waveguide A. The resonator can be in the form of closed-loop resonators, or as disk (**RD617, RD619**) or box (**RD521**) or spherical (not shown) shaped resonators as shown by device **RZD600** in FIG. 7E-2. Preferably, for these resonators, the center parts of the closed-loops are solid
20　　and either whispering-gallery modes or modes formed by repeated reflection from the resonator side walls are utilized to achieve optical resonances. The coupling to the resonators can be through a gap of low refractive index or a small joint in the form of a MMI coupler as illustrated by device **RZG600** in FIG. 7E-3 for which the coupling region (Wc1) represents such an MMI
25　　coupler. It should be understood that the devices **RZ600, RZD600, RZG600** are otherwise functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are generally applicable to the devices **RZ600, RZD600,** and **RZGG600** (except with figure labels now carrying prefixes RZ, RZD, and RZG, respectively).

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viiii). PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

As mentioned above, the optical waveguide in either the directional coupler configuration or the MMI configuration or the resonator configuration I or resonator configuration II may be implemented in the form of a photonic (PBG) structure. For the case of the directional coupler configuration, the PBG structure is shown by device **PC600** in FIG. 7F-1. The photonic-bandgap structure preferably includes a photonic bandgap waveguide A **PC602** and a photonic bandgap waveguide B **PC604**. The photonic bandgap PBG Waveguide A or B preferably includes a series of periodically placed holes formed by low refractive index materials outside the waveguiding region with high refractive index. As is known to those skilled in the art, these series of holes form a forbidden wavelength gap for the propagation of electromagnetic field, resulting in light confining in the region identified as photonic bandgap waveguide A or B. For example, for a refractive contrast of n=3.8 (Black region) to n=1 (white region), the vertical distance between center of the hole to center of the hole can be 0.527 microns, the horizontal distance between the center of the hole to center of the hole can be 0.608 microns, the diameter of the holes can be 0.4 microns, which will provide a photonic bandgap at about a 1.5 μm (or 1500nm) wavelength. The interaction length ℓ is chosen to achieve maximal energy coupling. The photonic bandgap waveguide B **PC604** preferably includes an active medium **PC608**, which is illustrated as a gray region in FIG. 7F-1. Photonic bandgap waveguide A **PC602** or B **PC604** in device **PC600** functions as waveguide A **602** or B **604** in device **600**. It should be understood that the device **PC600** is otherwise functionally and operationally identical to the device **600** and descriptions and comments relating to the device **600** are generally applicable to device **PC600** (except with figure labels now carrying prefix PC).

Similarly, the MMI configuration may be implemented in the form of a photonic bandgap structure as shown by device **PM600** in FIG. 7F-2. It should be understood that the device **PM600** is otherwise functionally and

operationally identical to the device **M600** and descriptions and comments relating to the device **M600** are generally applicable to device **PM600**. Likewise, the resonator configuration may be implemented in the form of a photonic bandgap structure. As an example, the photonic bandgap

5   implementation of resonator configuration I is shown by device **PRD600** in FIG. 7F-3. As is well known to those skilled in the art, resonators can be formed with photonic-bandgap structures by removing a single hole (as is the case for FIG. 7F-3) or groups of holes (not shown). It should be understood that the device **PRD600** is otherwise functionally and operationally identical to

10   the device **RD600** and descriptions and comments relating to the device **RD600** are generally applicable to device **PRD600** (except with figure labels now carrying prefix PRD). The photonic bandgap implementation of resonator configuration II can likewise be realized by replacing waveguides and resonators with photonic bandgap implementation of waveguides and

15   resonators in a manner similar to that demonstrated by the photonic bandgap implementation of configuration I.

It should be understood that the dimensions and materials for the devices are presented for purposes of illustrating a useful embodiment of the devices **M600, R600, RM600, RD600, RZ600, RZD600, RZG600, PC600,**

20   **PM600,** and **PRD600** are not intended to limit other exemplary embodiments of any exemplary device, or the devices **M600, R600, RM600, RD600, RZ600, RZD600, RZG600, PC600, PM600,** and **PRD600.** A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety

25   of materials can be used, for examples, the waveguides do not have to be semiconductor and may be optical fibers or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved), the active medium does not have to be semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite

30   gain/loss/transparency properties are achived), and the resonators do not have to be semiconductor but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the

shape of the Waveguides, MMI Structures, Photonic Bandgap Structures, or Resonators do not generally have to be linear, circular, parallel, or regular in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

It should be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the refractive index of the active medium could occur when the active medium changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the working of these devices include those cases whereby both the gain/transparency/loss property as well as the refractive-index property of the active medium are used in bringing about the device opertation.

C.   EXEMPLARY DEVICE 3

FIG. 8A illustrates a first embodiment **700** of a phosistor device employing directionally coupled waveguides. This device has very similar geometry as exemplary device **1** but with the active medium operated in the loss mode. The device can perform as a switching element and can in particular switch or convert a stream of slow or ultrafast (picosecond, femtosecond) optical pulses at low energy and long wavelength to a stream of slow or ultrafast optical pulses at comparatively high energy (comparatively short wavelength). The device **700** is not limited to use as a switching element and can be utilized, for example, as an all-optical logic gate, a light intensity amplifier, a photon duplicator, a light intensity modulator, a light intensity regulator, an optical phase shifter, a lossless signal tap, a quantum-nondemolition (QND) detector, and a variable optical attenuator. It should be understood that these exemplary applications of device **700** are intended to illustrate the wide range of uses for device **700**, and are not intended to limit the applications of other exemplary embodiments of device **700** to these

examples. The device can be referred to as an "Input-Arm-Loss-Gate Low-to-High-Energy Inversion Phosistor" (ILLH Phosistor **700**).

ILLH Phosistor **700** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **702** and a second pathway of light consisting of the spatial region occupied by Waveguide B **704**. A third Waveguide **706** is included in Phosistor **700** for coupling an input optical pulse to the Waveguide A **702** but which is otherwise not central to the operation of Phosistor **700**. The Waveguide A **702** preferably includes an active medium **708**. As described above, Waveguide A **702** can be implemented as waveguide **430** with active medium **420** in a useful embodiment, and waveguide B **704** and the third waveguide **706** can be implemented as waveguide **400**. The Waveguide A **702** preferably includes an input port APin2 **710** and an inner output port ASout2 **711**, and an output port ASout2a **712**. The Waveguide B **704** preferably includes an output port BPout2 **714**. The third Waveguide **706** preferably includes an input port ASin1 **716** which doubles as an output port ASout2b **724**. FIG. 8 illustrates that Waveguide A **702** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **704**, which has width W_B, so that a wave in Waveguide A can be coupled to a wave in Waveguide B. The terms "wave" and "light beam" are used interchangeably.

For the input port labeled "APin2" (**710**), "P" stands for Power-Supply beam, "A" refers to Waveguide A **702**, "in" refers to **710** being an input port, and "2" refers to the input wavelength being λ_2. For the inner output port labeled "ASout2" (**711**), "S" stands for Signal beam, "A" refers to Waveguide A **702**, "out" refers to it being an output port, "2" refers to the output wavelength being λ_2. For the output port labeled "ASout2a" (**712**), "S" stands for Signal beam, "A" refers to Waveguide A **702**, "out" refers to it being an output port, "2" refers to the output wavelength being λ_2, and "a" is used to distinguish this port **712** which is along Waveguide A **702**. For the output port labeled "ASout2b" (**724**), "S" stands for Signal beam, "A" refers to Waveguide A **702**, "out" refers to it being an output port, "2" refers to the output wavelength being

λ_2, and "b" is used to distinguish this port **724** which is along the third Waveguide **706**. For the output port labeled "BPout2" **(714)**, "P" stands for Power-Supply beam, "B" refers to Waveguide B **704**, "out" refers to it being an output port, and "2" refers to the output wavelength being λ_2. For the input

5   port labeled "ASin1" **(716)**, "S" stands for Signal beam, "A" refers to Waveguide A **702**, "in" refers to it being an input port, and "1" refers to the input wavelength being λ_1.

The input port APin2 **710** on the waveguide A **702** is configured to receive continuous wave (CW) light **718** having wavelength λ_2 (at λ_2) (CW

10   PWR IN λ_2). Under certain condition described below when the active medium on the waveguide reaches transparency and Waveguides A and B are optically transparent, part of the CW light at λ_2 **718** propagating along the Waveguide A **702** will be transferred to Waveguide B **704**. The CW light at λ_2 **718** then exits from Waveguide B **704** at the port BPout2 **714** as continuous

15   wave (CW) light at λ_2 (CW PWR BYPASS OUT λ_2) **720**.

The coupling length is defined as the length at which a wave in one waveguide maximally couples into another waveguide that is coupled to the first waveguide. In this device **700**, the interaction length ℓ, defined as the length of interaction between Waveguides A **702** and B **704**, is less than the

20   full coupling length ℓ_c so that $\ell < \ell_c$. In FIG. 8A, the interaction region between Waveguide B **704** and Waveguide A **702**, the region for which the two waveguides run in parallel and are separated by a small gap, is shown extending less than the full coupling length.

Since $\ell < \ell_c$, some portion of CW light at λ_2 **718** still propagates along

25   the Waveguide A **702** across the active medium **708** to the inner output port ASout2 **711**. As the portion of CW light at λ_2 **718** propagates across the active medium **708**, the portion of CW light at λ_2 **718** drives the active medium **708** to a state of transparency at λ_2. This state of the active medium **708** is analogous to Case D, as illustrated in FIG. 4D.

As shown in FIG. 8A, the length L of the active medium **708** is about half the interaction length ℓ ($L \cong \frac{\ell}{2}$). The length L of the active medium **708**

may be somewhat longer or shorter than half of ℓ. Varying the length L of the active medium **708** relative to the interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **700, 750** and are not intended to limit other exemplary embodiments of any exemplary device 3, or the devices **700, 750**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell < \ell_c$ is illustrated in this exemplary device, other choices of interaction length can be used to achieve similar device functions.

Also, it should be understood that the shape of the waveguides do not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an alternative location along waveguide A other than that illustrated in FIGs. 8A and 8B, and there can be more than one disconnected active medium areas along waveguide A. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel or have the same waveguide widths and dimensions as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of devices **700, 750**, for operation at 800nm wavelength range, the wavelength λ_1 can be at 820nm, λ_2 can be at 800nm, and the Waveguides A **702** can be implemented as the Waveguide **430** with an active medium 420 illustrated in FIGS. 5B and 5C and waveguide

B **704** can be implemented as Waveguide **400** in FIG. 5A, in an $Al_xGa_{1-x}As$ embodiment for the waveguide core having alloy composition x at 0.3 giving a bandgap energy of around 690nm. Thus the core material is transparent at the wavelength λ_2 of 800nm. When the active medium is fully de-excited, the active medium absorbs light at both 800nm and 820nm wavelengths. The active medium is an essentially three-level medium described in FIG. 4A-D for which electrons are free to relax from the upper-energy level corresponding to the 800nm absorption to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of devices **700, 750** for operation at 1500nm wavelength range, the wavelength λ_1 can be at 1500nm, λ_2 can be at 1480nm, and the Waveguide A **702** can be implemented as the Waveguide 430 with active medium **720** illustrated in FIGS. 5B and 5C and Waveguide B **704** can be implemented as the Waveguide **400** illustrated in 5A, in an $In_{1-x}Ga_xAs_{1-y}P_y$ embodiment for the waveguide core having alloy compositions x=0.16 and y=0.67 giving a bandgap energy of around 1100 nm. Thus the core material is transparent at the wavelength λ_1 of 1480nm. When the active medium is fully de-excited, the active medium absorbs light at both 1480nm and 1500nm wavelengths. The active medium is an essentially three-level medium described in FIG. 4A-D for which electrons are free to relax from the upper-energy level corresponding to the 1480nm absorption to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for operation at the 1500nm wavelength range, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. FIGS. 8A & 8B illustrate that Waveguide A **702** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **704**, which has width W_B. In this exemplary embodiment, the Waveguide A **702** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_g from Waveguide B **704** of 0.4

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μm, while Waveguide B **704** has width W_B equal to 0.4 μm. In this exemplary embodiment, ℓ_c is 15 μm and ℓ is 12 μm, so that $\ell < \ell_c$.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **700, 750** and are not intended to limit other exemplary embodiments of any exemplary device 3, or the devices **700, 750**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i). **Exemplary Device Operation**

An exemplary operation of the device is described below.

Continuous wave (CW) light having wavelength λ_2 (at λ_2) (CW PWR IN λ_2) **718** enters at the port APin2 **710** on the Waveguide A **702**. In the initial state, the active medium **708** along Waveguide A **702** is not excited and is in the state of loss analogous to CaseA, as illustrated in FIG. 4A. The CW light at λ_2 **718** propagates along the Waveguide A **702** and some of it is subsequently transferred to Waveguide B **704**. Since $\ell < \ell_c$, some portion of CW light at λ_2 **718** still propagates along the Waveguide A **702** across the active medium **708** to the inner output port ASout2 **711**. As the portion of CW light at λ_2 **718** propagates across the active medium **708**, the portion of CW light at λ_2 **718** will drive the active medium **708** to a state of transparency at λ_2 if this portion of CW light at λ_2 **718** has a high enough intensity. This state of the active medium **708** is analogous to Case D, as illustrated in FIG. 4D.

The portion of CW light at λ_2 **718** will propagate across the active medium **708** to port ASout2 **711** as light beam **713** and be subsequently divided to exit ports ASout2a **712** and ASout2b **724**. If the coupling of energy from the port ASin1/ASout2b **716/724** to Waveguide A **702** (or equivalently to port ASout2 **511**) is a 50/50 coupler, then the energy coupling ratio for light

propagating in the opposite direction (i.e. port **511** to port **716/724**) will also be 50/50. As a result, about 50 percent of λ_2 **723** at port ASout2 **711** will go to λ_2**726** at port ASin1/ASout2b **716/724** and 50 percent of λ_2 **723** at port ASout2 **711** will go to λ_2**728** at port ASout2a **712**.

5   The input port ASin1 **716** on the third Waveguide **706** effectively serves as another input port of Waveguide A **702**, and is the input signal port for pulsed light having wavelength λ_1 (SIGNAL IN λ_1) **722**. The pulsed light λ_1 **722** entering the port ASin1 **716** will de-excite or relax the active medium **708**, providing loss at the operating wavelength λ_2 to the active medium **708**

10   located in Waveguide A **702**. This state of the active medium **708** is analogous to Case C, as illustrated in FIG. 4C.

The CW light at λ_2 **718** from input port APin2 **710** loses energy in the active medium **708** so that the portion of CW light at λ_2 **718** no longer propagates out of the active medium **708** and thus no longer propagates

15   towards port ASout2 **711** or subsequently ports ASout2a **712** and ASout2b **724**. Preferably, all signals at λ_2 (SIGNAL OUT λ_2 **726**, SIGNAL OUT λ_2**728**) out of the first Waveguide A **702** are substantially reduced when a pulsed of light at λ_1 **722** is present.

In the case of FIG. 8A the net effect is that the pulsed light at λ_1 **722**

20   into port ASin1 **716** generates a negatively going signal pulse of light (light with a reduced intensity during the pulse duration) at λ_2 **713** exiting waveguide section ASout2 **711**, which proceeds to split its energy to a negatively going signal pulse of light at λ_2 **726** exiting port ASout2b **716** and a negatively going signal pulse of light at λ_2 **728** exiting port ASout2a **712**.

25   While not essential for the basic operation of the device **700**, an improved version **750** of the device **700** can be achieved via using a frequency-selective coupler such as grating or a small resonator. Such a frequency dependent coupler is called a dichroic filter or coupler and is shown as part of device **750** in FIG. 8B, replacing Waveguide **706** of FIG. 8A. The dichroic filter **756** will

couple **most of** the pulsed light λ_1 **772** entering the port ASin1 **766** to Waveguide A **702** but not λ_2. In this case, **most of** λ_2 (SIGNAL OUT λ_2) **778** will not couple from Waveguide A **702** to the port ASin1 **766** and will instead propagate preferably its energy to port ASout2a **762**. It should be understood that the device **750** is otherwise functionally and operationally identical to the device **700** and descriptions and comments relating to the device **700** are applicable to device **750**. As in device 1, alternatively, a polarization dependent coupler or a mode-selective coupler can be used to couple pulsed light λ_1 **772**.

It should be understood that the energy exiting the port BPout2 **714** (as continuous wave (CW) light at λ_2 (CW PWR BYPASS OUT λ_2) **720** can be designed to be not substantially affected in this entire process. The energy exiting the port BPout2 **714** of the ILLH Phosistor **700, 750** of FIGS. 8A and 8B is capable of being reused to power another phosistor. This feature is analogous to the supply voltage in electronic logic and switching circuitry.

It should be understood that the speed of switching can be fast as the active medium **708** when in the loss state at λ_2 (Case C in FIG..4C) will be driven back to the transparency state at λ_2 (Case D in FIG. 4D) rapidly by the light at λ_2 **718** passing through the loss medium **708** when pulsed light at λ_1 **722, 772** is removed. The state of the active medium **708** is again analogous to Case D, as illustrated in FIG. 4D.

ii).   Comments

It should be understood that in the typical operation of Phosistors, including the useful embodiments **700, 750**, one or more light inputs or outputs are described as continuous wave (CW) light. The light can otherwise be a pulsed light in some specific applications. For the purpose of illustration and not limitation it is taken as CW light.

The pulsed light at λ_1 **722** entering the port ASin1 **716** will de-excite the active medium **708**, providing loss at the operating wavelength λ_2 to the active medium **708** located in Waveguide A **702**.

It should be understood that the pulsed light at λ_1 **722, 772** can be input to the active medium **708** on Waveguide A **702** in any manner of implementation, in addition to the input structures **706** and **756** described in FIGS. 8A and 8B. For example, it can impinge on the active medium from outside the waveguides (e.g. from the top at a direction perpendicular to waveguide A).

Since the active medium **708** of devices **700, 750** of FIGS. 8A and 8B is operated at the absorbing or loss mode, this phosistor has a "loss gate". This gate is in the input arm (Waveguide A **702**).

It should be understood that due to the signal inversion of this device, i.e. a pulse at λ_1 in ("high" energy) causes a negatively going signal pulse of light at λ_2 out ("low" energy), and, conversely, while no pulse at λ_1 is input ("low" energy), a pulse at λ_2 will be output ("high" energy). Thus, this device can function as an inverter.

iii). MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator configuration for device 3 would be topologically similar to the MMI/Resonator configuration of Device 1. As in device 1, it should be understood that the MMI/Resonator Configuration Devices are otherwise functionally and operationally identical to the device **700** and descriptions and comments relating to the device **700** are generally applicable to the MMI/Resonator Configuration Devices.

iv). PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator configuration of device 3 would be topologically similar to the PBG implementations for the Coupler/MMI/Resonator configuration of device 1. As in device1, it should be understood that the PBG implementations for the Coupler/MMI/Resonator configuration of device 3 are otherwise functionally and operationally identical to the device **700** and descriptions and comments relating to the device **700** are generally applicable to the PBG implementations for the Coupler/MMI/Resonator configuration of device 3.

It should be understood that, as in the above embodiments, the dimensions and materials for the devices are presented for purposes of illustrating a useful embodiment of the device **700** and its MMI/PBG/Resonator versions, and are not intended to limit other exemplary embodiments of any exemplary device, or the device **700** its MMI/PBG/Resonator versions. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety of materials can be used, for examples, the waveguides do not have to be semiconductor and may be optical fibers or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved), the active medium does not have to be semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite gain/loss/transparency properties are achived), and the resonators do not have to be semiconductor but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the shape of the Waveguides, MMI Structures, Photonic Bandgap Structures, or Resonators do not generally have to be linear, circular, parallel, or regular in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

It should be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the

refractive index of the active medium could occur when the active medium changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the working of these devices include those cases whereby both the gain/transparency/loss property as well as the refractive-index property of the active medium are used in bringing about the device operation.

D.   EXEMPLARY DEVICE 4

FIG. 9 illustrates a fourth general embodiment **800** of a phosistor device employing directionally coupled waveguides. This device has very similar geometry to exemplary device 2 but with the active medium operated in the gain mode, the device can perform as a switching element and can in particular switch or convert a stream of slow or ultrafast (picosecond, femtosecond) optical pulses at high energy and short wavelength to a stream of slow or ultrafast optical pulses at comparatively low energy (comparatively long wavelength). The device **800** is not limited to use as a switching element and can be utilized, for example, as an all-optical logic gate, a light intensity amplifier, a photon duplicator, a light intensity modulator, a light intensity regulator, an optical phase shifter, a lossless signal tap, an optical detector, and a variable optical attenuator. It should be understood that these exemplary applications of device **800** are intended to illustrate the wide range of uses for device **800**, and are not intended to limit the applications of other exemplary embodiments of device **800** to these examples. The device can be referred to as an "Output-Arm-Gain-Gate High-to-Low-Energy Phosistor" (OGHL Phosistor **800**).

OGHL Phosistor **800** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **802** and a second pathway of light consisting of the spatial region occupied by Waveguide B **804**. The Waveguide B **804** preferably includes an active medium **808**. As described above, Waveguide B **804** can be implemented as waveguide **430** with active medium **420** and Waveguide A **802** can be implemented as

waveguide **400** in a useful embodiment. The Waveguide A **802** preferably includes an input port APin1 **810** and an output port ASout1 **812**. The Waveguide B **804** preferably includes an input port BSin2 **806** and an output port BPout1 **814** which doubles as a possible input port (not shown in FIG. 9). FIG. 9 illustrates that Waveguide A **802** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **804**, which has width W_B, so that a wave in Waveguide A can be coupled to a wave in Waveguide B. The terms "wave" and "light beam" are used interchangeably.

For the input port labeled "APin1" (**810**), "P" stands for Power-Supply beam, "A" refers to Waveguide A **802**, "in" refers to **810** being an input port, and "1" refers to the input wavelength being λ_1. For the output port labeled "ASout1" (**812**) , "S" stands for Signal beam, "A" refers to Waveguide A **802**, "out" refers to **812** being an output port, "1" refers to the output wavelength being λ_1. For the input port labeled "BSin2" (**806**), "S" stands for Signal beam, "B" refers to Waveguide B **804**, "in" refers to **806** being an input port, and "2" refers to the input wavelength being λ_2. For the output port labeled "BPout1" (**814**), "P" stands for Power-Supply beam, "B" refers to Waveguide B **804**, "out" refers to **814** being an output port, and "1" refers to the output wavelength being λ_1.

The input port APin1 **810** on the Waveguide A **802** is configured to receive continuous wave (CW) light **818** having wavelength λ_1 (at λ_1) (CW PWR IN λ_1). Under certain condition described below when the active medium on the waveguide reaches transparency and Waveguides A and B are optically transparent, most of the CW light at λ_1 **818** propagating along the Waveguide A **802** will be transferred to Waveguide B **804** after a coupling length ℓ_c. The CW light at λ_1 **818** then exits from Waveguide B **804** at the port BPout1 **814** as CW light at λ_1 (CW POWER OUT) **820**.

The coupling length is defined as the length at which a wave in one waveguide maximally couples into another waveguide that is coupled to the

first waveguide. In this device **800**, the interaction length ℓ, defined as the length of interaction between Waveguides A **802** and B **804**, is equal to the full coupling length ℓ_c so that $\ell = \ell_c$.

As shown in FIG. 9, the length L of the active medium **808** is about the interaction length ℓ ($L \cong \ell$). The length L of the active medium **808** may be somewhat longer or shorter than ℓ. Varying the length L of the active medium **808** relative to the interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **800** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **800**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell = \ell_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ_c (or multiple odd numbers of ℓ_c) without affecting the general operating principle of the device.

Also, it should be understood that the shape of the waveguides do not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an alternative location along waveguide B other than that illustrated in FIG. 9, and there may be more than one disconnected active medium areas along waveguide B. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel or have the same widths and dimensions as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of device **800**, for operation at 800nm wavelength range, the wavelength λ_1 can be at 820nm, λ_2 can be at 800nm, and the Waveguides A **802** can be implemented as the Waveguide **400** illustrated in FIG. 5A and waveguide B **804** can be implemented as Waveguide **430** with an active medium **420** illustrated in FIGS. 5B and 5C, in an $Al_xGa_{1-x}As$ embodiment having alloy composition x = 0.3 giving a bandgap energy of around 690nm. Thus the core material is transparent at the wavelength λ_2 of 800nm. The active medium absorbs light at 800nm and 820nm wavelengths when the active medium is fully de-excited, and corresponds to an essentially three-level medium described in FIG. 4A-D for which electrons are free to relax from the upper-energy level corresponding to the 800nm absorption to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of devices **800**, for operation at 1500nm wavelength range, the wavelength λ_1 can be at 1500nm, λ_2 can be at 1480nm, and the Waveguide A **802** can be implemented as the Waveguide **400** illustrated in FIG. 5A and Waveguide B **804** can be implemented as the Waveguide **430**. Both have an active medium **420** illustrated in FIGS. 5B and 5C, in an $In_{1-x}Ga_xAs_{1-y}P_y$ embodiment having alloy compositions x=0.16 and y=0.67 giving a bandgap energy of around 1100 nm. Thus the core material is transparent at the wavelength λ_1 of 1480nm. The active medium absorbs light at 1480nm and 1500nm wavelengths when the active medium is fully de-excited, and corresponds to an essentially three-level medium described in FIG. 4A-D for which electrons are free to relax from the upper-energy level corresponding to the 1480nm absorption to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for operation at the 1500nm wavelength range, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. FIG. 9 illustrates that Waveguide A **802** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **804**, which has width W_B. In this exemplary embodiment,

the Waveguide A **802** has width W$_A$ equal to 0.4 μm and is located at an approximately parallel distance W$_g$ from Waveguide B **804** of 0.4 μm, while Waveguide B **804** has width W$_B$ equal to 0.4 μm. In this exemplary embodiment, ℓ_c and ℓ are each 15 μm.

5   It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **800** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **800**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the

10   fabrication materials, processes or technologies that are employed.

i):   Exemplary Device Operation

15   There are various modes for which this device may function. Below, we will describe three exemplary and useful operating modes of the device.

First Exemplary Operating Mode

20   In the first exemplary and useful operating mode of the device, continuous wave (CW) light having wavelength λ_1 (at λ_1) (CW PWR IN λ_1) **818** enters at the port APin1 **810** on the Waveguide A **802**. In the initial state, the active medium **808** along Waveguide B **804** is not excited and is in the state of loss analogous to Case A, as illustrated in FG. 4A. The CW light at λ_1

25   **818** propagates along the Waveguide A **802** and some of its energy is leaked to Waveguide B **804** through evanescent coupling. As the portion of CW light at λ_1 **818** reaches the active medium **808** on Waveguide B, it drives the active medium **808** to a state of transparency at λ_1. The intensity of λ_1 must be high enough so that $I_1 > (1/\eta)I_{1Sat}$. That is, the intensity of the light at λ_1 must

30   exceed the saturation intensity divided by η, the effective percentage of

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leakage power to the Waveguide B **804** needed to bring the active medium in waveguide B to the state of transparency when there is no pulsed light at λ_2 **822** entering the port BSin1 **806** (i.e., an input off state). This state of the active medium **808** is analogous to Case C, as illustrated in FIG. 4C.

5   The input port BSin2 **806** on Waveguide B **804** is the input signal port for pulsed light having wavelength λ_2 (SIGNAL IN λ_2) **822**. The pulsed light λ_2 **822** entering the port BSin2 **806** will excite the active medium **808**, providing gain at the operating wavelength λ_1 to the active medium **808** located in Waveguide B **804**. This state of the active medium **808** is

10   analogous to Case B, as illustrated in FIG. 4B. The CW light at λ_1 **818** from input port APin1 **810** gains energy in the active medium **808** so that a portion of the CW light at λ_1 **818** does not transfer to Waveguide B **804** and thus does not exit from the output BPout1 **814**. Rather, this portion of the CW light at λ_1 **818** propagates through Waveguide A **802** and exits out of output port ASout1

15   **812** as a pulse of light at λ_1 (SIGNAL OUT λ_1) **828**.

         When pulsed light at λ_2 **822** is removed, the active medium will be driven back to the transparency state at λ_1 (Case D in FIG. 4D) by the light at λ_1 **818** passing through the loss or absorbing medium **808**, and most of CW light at λ_1 **818** will transfer to Waveguide B **804** and thus will again exit from

20   the output on BPout1 **814**. The net effect in this first exemplary and useful operating mode of the device of FIG. 9 is that in the initial state, most of the CW light at λ_1 **818** from input port APin1 **810** couples to Waveguide B **804** and exits out of output port BPout1 **814** as CW λ_1 **820**. The pulsed light at λ_2 **822** into port BSin2 **806** generates a positively going pulse of light at λ_1 **828**

25   exiting port ASout1 **812** and a positively going pulse of light at λ_1 **820** exiting port BPout1 **814**. Upon cessation of the pulsed light at λ_2 **822**, the light at λ_1 **828** returns to its initial state and most of the light at λ_1 **828** exits out of output port BPout1 **814** as CW λ_1 **820**.

Second Exemplary Operating Mode

In the second exemplary and useful operating mode of the device, the intensity of λ_1 **818** is lower than the intensity required to driving the active medium to the state of transparency at λ_1. In this case the CW light at λ_1 **818** will not drive the medium to transparency by itself. In the absent of the pulsed light at λ_2 **822** the active medium along waveguide B **804** will decay back to the state of loss at λ_1. As a result, most of the CW light at λ_1 **818** will not transfer from Waveguide A **802** to waveguide B **804** and will instead propagate along Waveguide A 802 and have most of its energy exiting port ASout1 **812**. When pulsed light λ_2 **822** is introduced with an appropriate light intensity, the pulsed light λ_2 **822** entering the port BSin2 **806** will excite the active medium **808**, providing transparency at the operating wavelength λ_1 to the active medium **808** along Waveguide B **804**. This state of the active medium **808** is analogous to Case C, as illustrated in FIG. 4C. After the active medium is in the state of transparency, most of the energy of the CW light at λ_1 **818** from input port APin1 **810** will transfer from Waveguide A **802** to Waveguide B **804** and will exit from the output BPout1 **814**. The net effect in this second exemplary and useful operating mode of the device of FIG. 9 is that in the initial state, most of the CW light at λ_1 **818** from input port APin1 **810** propagates through Waveguide A **802** and exits out of output port ASout1 **812** as CW λ_1 **828**. The pulsed light at λ_2 **822** into port BSin2 **806** generates a positively going pulse of light at λ_1 **820** exiting port BPout1 **814** and a negatively going pulse of light at λ_1 **828** exiting port ASout1 **812**. Upon cessation of the pulsed light at λ_2 **822,** and after the medium has enough time to decay to the state of loss, the light at λ_1 **828** returns to its initial state most of the light at λ_1 **828** exits out of output port ASout1 **812** as CW λ_1 **828**.

In order for light beam λ_2 **822** to interact with the active medium effectively, it may be desirable that they do not couple much of their energy

from waveguide B to waveguide A, though such coupling will not affect the general operating principle of the device. This can be achieved for example by placing light beams λ_2 **822** in a polarization different from that of light beam λ_1 **818**, and by having weak or negligible coupling between waveguides A and

5   B for light beams λ_2 **822** but strong coupling for light beam λ_1 **818**. That is, waveguides A and B a polarization dependent coupler. Alternatively, this can be achieved by having waveguides A and B be a mode selective coupler and by having light beams λ_2 **822** to be in a different propagating waveguide modes (e.g. to be in the first order propagating mode) from that of light

10   beam λ_1 **818** (e.g. to be in the second order propagating mode).

Third Exemplary Operating Mode

In the third exemplary and useful operating mode of the device, the

15   situation is essentially the same as the second operating mode of the device, except that the intensity of pulsed light λ_2 **822** is so high as to drive the active medium to a state of gain. This state of the active medium is analogous to Case B in FIG. 4B. In this case, CW light at λ_1 **818** from input port APin1 **810**, beside transferring part of its energy from Waveguide A **602** to Waveguide B

20   **604**, will gain energy in the active medium **808** of waveguide B so that a portion of the CW light at λ_1 **818** does not transfer to Waveguide B **804** and will propagate through Waveguide A **802** and exit out of output port ASout1 **812** as a pulse of light at λ_1 (SIGNAL OUT λ_1) **828**. The net effect in this third exemplary and useful operating mode of device of FIG. 9 is that in the initial

25   state, most of the CW light at λ_1 **818** from input port APin1 **810** propagates through Waveguide A **802** and exits out of output port ASout1 **812** as CW λ_1 **828**. The pulsed light at λ_2 **822** into port BSin2 **806** generates a positively going pulse of light at λ_1 **820** exiting port BPout1 **814** and a pulse of light at λ_1 **828** exiting port ASout1 **812** that is a less negatively going pulse of light than

30   that of the second operating mode, or even a positively going pulse of light, if

the intensity of light at λ_2 **822** is high enough. Upon cessation of the pulsed light at λ_2 **822,** and after the medium has enough time to decay to the state of loss, the light at λ_1 **828** returns to its initial state and most of the light at λ_1 **828** exits out of output port ASout1 **812** as CW λ_1 **828.**

ii).   General Operation of the Device

An exemplary operation of the device can be illustrated via the result of computer simulation as shown in FIGs. 9A-1 and 9A-2. FIGs. 9A-1 and 9A-2 show the spatial distribution of the electric field strength for the light input at λ_2 **818** after propagating into waveguides A and B. The upper parts of FIGs. 9A-1 and 9A-2 are 2-D plots for which the brightness shows the relative field strength, and the lower parts of FIGs. 9A-1 and 9A-2 are 3-D plots for which the heights show the relative field strength. FIG 9A-3 shows the relative power at the output ports of waveguide A (port ASout2 **812**) and waveguide B (port BPout2 **814**) as a function of –gL (the product of the loss coefficient –g and the medium length L). In the figure, the output at ASout1 is shown as a dotted line, the output at BPout1 is shown as a dashed line, and the solid line is the sum of the outputs at ASout1 and BPout1 (i.e. the dashed line plus the dotted line). FIG. 9A-1 shows the situation when the gain medium is in the state of transparency (at a loss coefficient of 0 per μm or –gL=0). From FIG. 9A-1, it is evident that most of the energy of λ_2 **818** exits from Waveguide B **804** at the port BPout2 **814.** FIG. 9A-2 shows the situation when the medium is excited to the state of gain at λ_1 by the pulsed light at λ_2 **822** (at a gain coefficient of about 0.1 per μm or gL=1.5). From FIG. 9A-2, it is evident that additional energy of λ_1 exits from Waveguide A. FIGS. 9A-1 and FIG. 9A-2 show the two representative interference flux patterns of light for the device, which are dependent on the state of the active medium. In particular, one can switch between these two representative interference flux patterns of light by

changing the state of the active medium through the action of another light beam.

iii). Comments

In should be understood that in the typical operation of Phosistors, including the useful embodiment **800**, one or more light inputs and outputs are described as continuous wave (CW) light. The light can otherwise be a pulsed light in some specific applications. For the purpose of illustration and not limitation the light is taken as CW light.

It should also be understood that the speed of switching can be fast as the active medium **808**, when in the gain state at λ_1 (Case B in FIG. 4B), will be driven back to the transparency state at λ_1 (Case C in FIG. 4C) rapidly by the light at λ_1 **818** passing through the gain medium **808** when pulsed light at λ_2 **822** is removed. The state of the active medium **808** is again analogous to Case C, as illustrated in FIG. 4C.

Furthermore, it should be understood that the pulsed light at λ_2 **822** can be input to the active medium **808** on Waveguide B **804** in any manner of implementation. For example, it can impinge on the active medium from outside the waveguides (e.g. from the top at a direction perpendicular to waveguide B). Furthermore, the pulsed light at λ_2 **822** can also enter either input port BSin2 **806** or output port BPout1 **814** which doubles as a possible input port (not shown in FIG. 9). The problem of any mixing of light that might occur can be addressed with use of a dichroic filter or coupler (not shown). As in device 2, alternatively, a polarization dependent coupler or a mode-selective coupler can be used instead of a dichroic filter or coupler.

Since the active medium **808** of device **800** of FIG. 9 is operated at the gain mode, this phosistor has a "gain gate". This gate is in the output arm (Waveguide B **804**).

iv). Exemplary Device 4 as a Wavelength Multiplexer/De-Multiplexer or Wavelength Selective Switch

In another useful embodiment of device 4, the waveguide A and B have unequal widths W_A and W_B. As is well known to those skilled in the art, waveguide couplers with unequal waveguide widths will have strong

5   wavelength sensitivity. In particular, when the active medium is in the transparency state, only certain wavelengths of light will couple maximally from waveguide A to waveguide B, thus allowing the device to act not only as a switch but as a wavelength selective switch. Except for the difference in the waveguide widths providing wavelength sensitivity, this embodiment of the

10   device is otherwise functionally and operationally identical to the device **800** and descriptions and comments relating to the device **800** are generally applicable to this device.

v).   Multiple Waveguide Version of Device 4

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As a variation of geometry, device 4 can be realized in the form of a multiple waveguide device such as a three-waveguide structure. It should be evident to those skilled in the art that the three-waveguide device for device 4 would be topologically similar to the three-waveguide device of Device 2. As

20   in device 2, it should be understood that the three-waveguide device is otherwise functionally and operationally identical to the device **800** and descriptions and comments relating to the device **800** are generally applicable to the three-waveguide device. As in device 2, such a three- waveguide device can be generalized to a multiple–waveguide device.

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vi).   MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator I/Resonator II configuration for device 4 would be topologically similar to the

30   MMI/ Resonator I/Resonator II configuration of Device 2. As in device 2, it should be understood that the MMI/Resonator I/Resonator II Configuration Devices are otherwise functionally and operationally identical to the device

800 and descriptions and comments relating to the device **800** are generally applicable to the MMI/Resonator I/Resonator II Configuration Devices.

vii).   PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 4 would be topologically similar to the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 2. As in device 2, it should be understood that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 4 are otherwise functionally and operationally identical to the device **800** and the descriptions and comments relating to the device **800** are generally applicable to the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 4.

It should be understood that, as in the previous embodiment, the dimensions and materials for the devices are presented for purposes of illustrating a useful embodiment of the device **800** and its MMI/PBG/Resonator versions, and are not intended to limit other exemplary embodiments of any exemplary device, or the device **800** its MMI/PBG/Resonator versions. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety of materials can be used, for examples, the waveguides do not have to be semiconductors and may be optical fibers or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved), the active medium does not have to be a semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite gain/loss/transparency properties are achived), and the resonators do not have to be semiconductors but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the shape of the Waveguides,

MMI Structures, Photonic Bandgap Structures, or Resonators does not generally have to be linear, circular, parallel, or regular in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

It should also be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the refractive index of the active medium could occur when the active medium changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the working of these devices include those cases whereby both the gain/transparency/loss property as well as the refractive-index property of the active medium are used in bringing about the device operation.

E. EXEMPLARY DEVICE 5: A FLIP-FLOP BASED ON EXEMPLARY DEVICE 2

Several versions of Photonic Flip-Flops, Photonic logic gates, and Photonic Random Access Memory (RAM) with latching, enable, and reset devices can be constructed and implemented utilizing the exemplary embodiments 1 through 4.

For example, FIG. 10 illustrates a fifth general embodiment **1000** of a phosistor device employing directionally coupled waveguides. The device can operate as a flip-flop or storage element by management of, including optional switching of, streams of slow or ultrafast (picosecond, femtosecond) optical pulses of equivalent, comparable, or differing energies and wavelengths. The device can be referred to as a "Flip-Flop Memory State Phosistor" and in this exemplary embodiment **1000** as an "Output-Arm-Loss-Gate High-or-Low Energy Flip-Flop Phosistor".

Phosistor **1000** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **1002** and a second pathway of

light consisting of the spatial region occupied by Waveguide B **1004**. The Waveguide B **1004** preferably includes an active medium **1008**. As described above, Waveguide B **1004** can be implemented as waveguide **400** with active medium **420** (see FIG. 5A) in a useful embodiment.

In an exemplary embodiment, the Waveguides A and B **1002, 1004** can each be implemented as the Waveguide **400** illustrated in FIG. 5A, in an $Al_xGa_{1-x}As$ embodiment having alloy composition x at 0.3 giving a bandgap energy of around 690nm.

In an exemplary embodiment, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. FIG. 10 illustrates that Waveguide A **1002** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **1004**, which has width W_B. In an exemplary embodiment, the Waveguide A **1002** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_g from Waveguide B **1004** of 0.4 μm, while Waveguide B **1004** has width W_B equal to 0.4 μm.

It should be understood that these dimensions and exemplary lengths are presented for purposes of illustrating a useful embodiment of the device **1000** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1000**. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. Also, it should be understood that the shape of the waveguides does not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel as long as the desired effect of wave-coupling is achieved.

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The coupling length ℓ_c is defined as the length at which a wave in one waveguide maximally couples into another waveguide that is coupled to the first waveguide. In this device **1000**, the interaction length ℓ, defined as the length of interaction between Waveguides A **1002** and B **1004**, is

5   approximately equal to the full coupling length ℓ_c so that $\ell = \ell_c$. In an exemplary embodiment, ℓ_c and ℓ are each 15 μm. As shown in FIG. 10, the length L of the active medium **1008** is about the interaction length ℓ ($L \cong \ell$). The length L of the active medium **1008** may be somewhat longer or shorter than ℓ. Varying the length L of the active medium **1008** relative to the

10   interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that these dimensions and exemplary lengths are presented for purposes of illustrating a useful embodiment of the device **1000** and are not intended to limit other exemplary embodiments of any

15   exemplary device, or the device **1000**. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell = \ell_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ_c (or multiple odd numbers of ℓ_c)

20   without affecting the general operating principle of the device.

The Waveguide A **1002** preferably includes an input port AENABLEin **1010** and an output port ARESETout **1012**. The Waveguide B **1004** preferably includes an input port BSETin **1006** and an output port BSETout **1014** which can double as an input port for a "reset pulse" (this case is not

25   illustrated in FIG. 10). While not essential for the basic operation of this flip-flop phosistor, a frequency-selective coupler such as a grating or a small resonator can be used to couple a "reset" pulse. Alternatively, a polarization dependent beam splitter or coupler that can be used to couple the "reset" pulse of light pulses of different polarization are utilized to operate the device.

30   Or as in device 1 or 2, alternatively, a mode-selective coupler can be used instead of the polarization dependent coupler. In the version of the Phosistor

1000 illustrated in FIG. 10, a dichroic filter **1030** is used to couple a "reset" pulse entering an input port BRESETin **1016** to the Waveguide B. It should be understood that embodiments of the Phosistor **1000** are not limited to the use of this frequency-selective filter. In other embodiments, for example, Waveguide B **1004** is capable of receiving a "reset" pulse into port **1006**, **1014** or both, with no separate frequency dependent coupler or filter. Still other embodiments use one or more frequency dependent couplers or filters to couple input signals, including but not limited to "reset" pulses into the appropriate waveguide.

The input port AENABLEin **1010** on the Waveguide A **1002** is configured to receive pulsed light having wavelength λ_L (at λ_L) (ENABLE SIGNAL IN λ_L) **1018**. The pulsed light at λ_L **1018** can be referred to as an "enable" signal since the introduction of this signal sends the flip-flop Phosistor **1000** into an "enable" state, or "enables" the Phosistor **1000**. Depending on the state of the Phosistor **1000**, light can be output from the output port BSETout **1014** as pulsed light having wavelength λ_L (SET STATE OUT λ_L) **1020**. Light is also capable of being output from the output port ARESETout **1012** as pulsed light having wavelength λ_L (RESET STATE OUT λ_L) **1028**.

The input port BSETin **1006** on the Waveguide B **1004** is configured to receive pulsed light having wavelength λ_H (SET SIGNAL IN λ_H) **1022**. The pulsed light at λ_H **1022** can be referred to as a "set" signal or pulse since the introduction of this signal sends the flip-flop Phosistor **1000** into a "set" state, or "sets" the Phosistor **1000**. The input port BRESETin **1016** on the dichroic filter **1030** is configured to receive pulsed light having wavelength λ_{LL} (RESET SIGNAL IN λ_{LL}) **1024**. The pulsed light at λ_{LL} **1024** can be referred to as a "reset" signal or pulse since the introduction of this signal sends the flip-flop Phosistor **1000** into a "reset" state, or "resets" the Phosistor **1000**.

It should be understood that the output port BSETout **1014** of Waveguide B **1004** can also serve as the input signal port for pulsed light having wavelength λ_H (SET SIGNAL IN λ_H) **1022**. More generally, it should

be understood that the pulsed light at λ_H **1022** can be input to the active

medium **1008** on Waveguide B **1004** in any manner of implementation. For

example, it can impinge on the active medium from outside the waveguides

(e.g. from the top at a direction perpendicular to waveguide B). Furthermore,

5   the pulsed light at λ_H **1022** can also enter either input port BSETin **1006** or

output port BSETout **1014** which doubles as a possible input port (not shown

in FIG. 10). The problem of any mixing of light that might occur can be

addressed with use of a dichroic filter of coupler as described above for the

input port BRESETin **1016** or by using light of mutually orthogonal polarization

10   with use of a polarization dependent beam splitter or coupler. Or as in device

1 or 2, alternatively, a mode-selective coupler can be used instead of the

polarization dependent coupler.

Exemplary device 2 **600** of FIG. 7 was discussed above with reference

to the way in which the device **600** could be switched between two states, the

15   first state corresponding to Case "D" of FIG. 4D, and the second state

corresponding to Case "C" of FIG. 4C. In the case of Phosistor **1000**,

manipulating the intensity I_L of the pulsed light at λ_L **1018** can create an

additional operational state corresponding to Case "A" of FIG. 4A. This

operational state is exploited in Phosistor **1000**.

20   In a preferred embodiment, the Phosistor **1000** operates as a flip-flop

according to restrictions that are placed on the relative magnitudes of the

operating wavelengths λ_L, λ_H, and λ_{LL} of the light inputs **1018**, **1022**, and

1024, respectively. First, the pulsed light at λ_H **1022** (i.e., the "set" beam)

preferably has a wavelength λ_H that is shorter than or equal to the wavelength

25   λ_L of the pulsed light at λ_L **1018** (the "enable" beam), that is, $\lambda_H \leq \lambda_L$. Second,

the pulsed light at λ_{LL} **1024** (i.e., the "reset" beam) preferably has a

wavelength that is longer than the wavelength λ_L of the pulsed light at λ_L **1018**

as well as the pulsed light at λ_H **1022**, that is, $\lambda_{LL} > \lambda_L \geq \lambda_H$.

The former restriction ($\lambda_H \leq \lambda_L$) for the exemplary embodiment of

30   Phosistor **1000** has implications with regard to the two general wavelengths λ_1

and λ_2, where λ_1 has the longer wavelength as defined above with reference

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to exemplary devices 1-4. As such, the Phosistor **1000** can operate with $\lambda_L = \lambda_H = \lambda_1$, or $\lambda_L = \lambda_H = \lambda_2$, or $\lambda_L = \lambda_1$ and $\lambda_H = \lambda_2$.

i).   The Enable State

For this Enable state of Phosistor **1000**, the enable beam at λ_L **1018** is turned "on," while the set beam at λ_H **1022** and the reset beam at λ_{LL} **1024** are both "off."

To create the first operational state of the Phosistor Flip-Flop **1000** the pulsed light at λ_L **1018** (the "enable" beam) is turned "on" and is maintained at relatively low intensity so that the active medium **1008** will not be driven to transparency due to the small leakage from Waveguide A **1002** to Waveguide B **1004**. The intensity I_L of the light at λ_L **1018** is kept purposely low enough so that $I_L < (1/\eta)I_{LSat}$, that is, the intensity I_L does not exceed the saturation intensity divided by η , the effective percentage of leakage power to the Waveguide B **1004** needed to bring the active medium in waveguide B **1004** to the state of transparency when there is no set beam at λ_H **1022** entering the port BSETin **1006**. The enable beam at λ_L **1018** does not have a high enough intensity to drive the active medium **1008** in Waveguide B **1004** to transparency at λ_L by itself from Waveguide A **1002**. In this situation, most of the power of the light beam at λ_L will exit port ARESETout.

In this case, the active medium **1008** provides loss at λ_L **1018**. Essentially, the net result is that more electrons in the active medium **1008** relax from high energy states (i.e. spontaneously decay) than are excited to high energy states. This state of the active medium **1008** is analogous to Case A, as illustrated in FIG. 4A.

ii).   The Set State

For this Set state of Phosistor **1000**, the enable beam at λ_L **1018** is "on," the set beam at λ_H **1022** is turned "on," and the reset beam at λ_{LL} **1024**

remains "off." Once the set beam at λ_H **1022** is turned "on," the Phosistor **1000** is "latched" and remains in the Set state, even if the set beam at λ_H **1022** is turned "off," while the enable beam at λ_L **1018** is "on" and until the Phosistor is "reset."

By itself, the enable beam at λ_L **1018** does not have a high enough intensity to drive the active medium **1008** in Waveguide B **1004** to transparency at λ_L from Waveguide A **1002**. By design, the enable beam at λ_L **1018** requires the assistance of the set beam at λ_H **1022** to drive the active medium **1008** to transparency at λ_L. The set beam at λ_H **1022** preferably has a wavelength λ_H that is shorter than or equal to λ_L as described above.

The set beam at λ_H **1022** turns on and consequently drives the active medium **1008** to a state of transparency at λ_L. Now, the enable beam at λ_L **1018** propagates along the Waveguide A **1002** and is subsequently transferred to propagate across the active medium in Waveguide B **1004** after the coupling length ℓ_c. The enable beam at λ_L **1018** then exits from Waveguide B **1004** at the port BSETout **1014** as light at λ_L **1020**. This state of the active medium **1008** is analogous to Case D, as illustrated in FIG. 4D.

In effect, the set beam at λ_H **1022** latches the Phosistor **1000** flip-flop so that the active medium **1008** remains in a state of transparency at λ_L, even when the set beam at λ_H **1022** is turned off and is no longer present. That is, the enable beam at λ_L **1018** is purposely maintained at an intensity I_L that is too low to drive the medium **1008** to transparency at λ_L by itself, but the additional power latched to propagate through the active medium **1108** in Waveguide B **1004** by the set beam at λ_H **1022** is sufficient to maintain the transparency at λ_L once the set beam at λ_H **1022** is turned off and is no longer present.

iii).   The Reset State (Enable=1; Set=0; Reset=0→1→0)

For this Reset state of Phosistor **1000**, the enable beam at λ_L **1018** is "on," the set beam at λ_H **1022** is turned "off," and the reset beam at λ_{LL} **1024** is turned "on." Once the reset beam at λ_{LL} **1024** is turned "on," the Phosistor **1000** is "unlatched" or "reset." When the reset beam at λ_{LL} **1024** is turned "off," the Phosistor **1000** returns to the Enable state, while the enable beam at λ_L **1018** is "on."

The reset beam at λ_{LL} **1024** entering the port BRESETin **1016** will de-excite or relax the active medium **1008** on Waveguide B **1004**, providing loss at the operating wavelength λ_L to the active medium **1008**. This state of the active medium **1008** is analogous to Case C, as illustrated in FIG. 4C.

The enable beam at λ_L **1018** from input port AENABLEin **1010** loses energy in the active medium **1008** so that most of the pulsed light at λ_L **1018** does not transfer to Waveguide B **1004** and thus does not exit from the output on BSETout **1014**. Rather, most of the pulsed light at λ_L **1018** propagates through Waveguide A **1002** and exits mainly out of output port ARESETout **1012** as pulsed light at λ_L **1028** out of the first Waveguide A **1002**.

In the case of FIG. 10, the net effect is that once the Phosistor **1000** is enabled by the enable beam at λ_L **1018**, application of a pulse of light at λ_H **1022** (the set beam) into port BSETin **1006** generates light at λ_L **1020** exiting port BSETout **1014**. The Phosistor **1000** will remain latched in this set state until the application of a reset pulse of light at λ_{LL} **1024**, which in turn generates a light at λ_L **1028** exiting port ARESETout **1012**.

It should be understood that in accordance with standard logical operation of Set-Reset flip-flops, the Phosistor **1000** when utilized as a flip-flop, preferably, simultaneous application of set and reset pulses of light **1022**, **1024**, respectively, should be avoided.

It should be understood that in the typical operation of the Phosistors, including the useful embodiment **1000**, one or more light inputs and outputs are described as pulsed light. This light can otherwise take the form of

continuous wave (CW) light in some specific applications. For the purpose of illustration and not limitation it is taken as pulsed light.

Since the active medium **1008** of device **1000** of FIG. 10 is operated at the absorbing or loss mode, this phosistor has a "loss gate". This gate is in the output arm (Waveguide B **1004**).

iv). MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator I/Resonator II configuration for device 5 would be topologically similar to the MMI/ Resonator I/Resonator II configuration of Device 2. As in device 2, it should be understood that the MMI/Resonator I/Resonator II Configuration Devices are otherwise functionally and operationally identical to the device **1000** and descriptions and comments relating to the device **1000** are generally applicable to the MMI/Resonator I/Resonator II Configuration Devices.

v). PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 5 would be topologically similar to the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 2. As in device 2, it should be understood that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 5 are otherwise functionally and operationally identical to the device **1000** and descriptions and comments relating to the device **1000** are generally applicable to the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 5.

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F.   EXEMPLARY DEVICE 6: FLIP-FLOP BASED ON EXEMPLARY DEVICE 3

5   Another Photonic Flip-Flop can be constructed and implemented utilizing the exemplary device 3.

          For example, FIG. 11 illustrates a sixth general embodiment **1100** of a phosistor device employing directionally coupled waveguides. The device can operate as a flip-flop or storage element by management of, including optional

10   switching of, streams of slow or ultrafast (picosecond, femtosecond) optical pulses of equivalent, comparable, or differing energies and wavelengths. The device can be referred to as a "Flip-Flop Memory State Phosistor" and in this exemplary embodiment **1100** as an "Input-Arm-Loss-Gate High-or-Low Energy Flip-Flop Phosistor".

15   Phosistor **1100** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **1102** and a second pathway of light consisting of the spatial region occupied by Waveguide B **1104**. The Waveguide A **1102** preferably includes an active medium **1108**. As described above, Waveguide B **1104** can be implemented as waveguide **400** with active

20   medium **420** (see FIG. 5B and 5C) in a useful embodiment.

          In an exemplary embodiment, the Waveguides A and B **1102, 1104** can each be implemented as the Waveguide **400** illustrated in FIG. 5A, in an $Al_xGa_{1-x}As$ embodiment having alloy composition x at 0.3 giving a bandgap energy of around 690nm.

25   In an exemplary embodiment, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. FIG. 11 illustrates that Waveguide A **1102** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **1104**, which has width W_B. Preferably, the Waveguide A **1102** has width W_A equal to 0.4 μm

30   and is located at an approximately parallel distance W_g from Waveguide B **1104** of 0.4 μm, while Waveguide B **1104** has width W_B equal to 0.4 μm.

As with the previous embodiments, it should be understood that these dimensions and exemplary lengths are presented for purposes of illustrating a useful embodiment of the device **1100** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1100**. A

5   variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. Also, it should be understood that the shape of the waveguides does not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such

10   as waveguiding and wave-coupling. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel as long as the desired effect of

15   wave-coupling is achieved.

The coupling length ℓ_c is defined as the length at which a wave in one waveguide maximally couples into another waveguide that is coupled to the first waveguide. In this device **1100**, the interaction length ℓ, defined as the length of interaction between Waveguides A **1102** and B **1104**, is less than

20   the full coupling length ℓ_c so that $\ell < \ell_c$. In FIG. 11, the interaction section of Waveguides B **1104** and A **1102** is shown extending less than the full coupling length. In an exemplary embodiment, ℓ_c is 15 μm and ℓ is 12 μm, so that $\ell < \ell_c$. As shown in FIG. 11, the length L of the active medium **1108** is about half the interaction length ℓ ($L \cong \frac{\ell}{2}$). The length L of the active medium

25   **1108** may be somewhat longer or shorter than half of ℓ. Varying the length L of the active medium **1108** relative to the interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that these dimensions and exemplary lengths

30   are presented for purposes of illustrating a useful embodiment of the device

1100 and are not intended to limit other exemplary embodiments of any exemplary device, or the device 1100. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell < \ell_c$ is illustrated in this exemplary device, other choices for the interaction length can be used to achieve similar device functions.

The Waveguide A 1102 preferably includes an input port AENABLEin 1110 for an "enable signal." The Waveguide B 1104 preferably includes an input port for a "reset pulse". While not essential for the basic operation of this flip-flop phosistor, a frequency-selective coupler such as a grating or a small resonator can be used to couple the "reset" pulse. Alternatively, a polarization dependent beam splitter or coupler can be used to couple the "reset" pulse if light pulses of different polarization are utilized to operate the device. In the version of the Phosistor 1100 illustrated in FIG. 11, a dichroic filter 1130 is used to couple the "reset" pulse entering an input port BRESETin 1116 to the Waveguide B 1104.

Preferably, the Waveguide A 1102 further includes an output port ASETout 1114 which can double as an input port for a "set pulse" (this case is not illustrated in FIG. 11). While not essential for the basic operation of this flip-flop phosistor, a frequency-selective coupler such as a grating or a small resonator, or a polarization dependent beam splitter or coupler can be used to couple the "set" pulse. Or as in device 1 or 2, alternatively, a mode-selective coupler can be used instead of the polarization dependent coupler. In the version of the Phosistor 1100 illustrated in FIG. 11, a dichroic filter 1126 is used to couple a "set" pulse into an input port ASETin 1106. Finally, the Waveguide B 1104 preferably includes an output port BRESETout 1112.

It should be understood that embodiments of the Phosistor 1100 are not limited to the use of the frequency-selective filters 1126, 1130. In other embodiments, for example, Waveguide A 1102 is capable of receiving "reset" or "set" pulses into ports 1110, 1114 or both, with no separate frequency dependent coupler or filter. Still other embodiments use one or more frequency dependent couplers or filters, or polarization dependent beam

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splitters or couplers to couple input signals, including but not limited to "reset" pulses and "set" pulses into the appropriate waveguide. Or as in device 1 or 2, alternatively, a mode-selective coupler can be used instead of the polarization dependent coupler.

5   The input port AENABLEin **1110** on the Waveguide A **1102** is configured to receive pulsed light having wavelength λ_L (at λ_L) (ENABLE SIGNAL IN λ_L) **1118**. The pulsed light at λ_L **1118** can be referred to as an "enable" signal since the introduction of this signal sends the flip-flop Phosistor **1100** into an "enable" state, or "enables" the Phosistor **1100**.

10 Depending on the state of the Phosistor **1100**, light can be output from the output port ASETout **1114** as pulsed light having wavelength λ_L (SET STATE OUT λ_L) **1120**. Light is also capable of being output from the output port BRESETout **1112** as pulsed light having wavelength λ_L (RESET STATE OUT λ_L) **1128**.

15   The input port ASETin **1106** on the dichroic filter **1126** is configured to receive pulsed light having wavelength λ_H (SET SIGNAL IN λ_H) **1122**. The pulsed light at λ_H **1122** can be referred to as a "set" signal or pulse since the introduction of this signal sends the flip-flop Phosistor **1100** into a "set" state, or "sets" the Phosistor **1100**. The input port BRESETin **1116** on the dichroic

20 filter **1130** is configured to receive pulsed light having wavelength λ_{LL} (RESET SIGNAL IN λ_{LL}) **1124**. The pulsed light at λ_{LL} **1124** can be referred to as a "reset" signal or pulse since the introduction of this signal sends the flip-flop Phosistor **1100** into a "reset" state, or "resets" the Phosistor **1100**.

        It should be understood, however, that the pulsed light at λ_H **1122** can

25 be input to the active medium **1108** on Waveguide A **1102** in any manner of implementation. For example, it can impinge on the active medium from outside the waveguides (e.g. from the top at a direction perpendicular to waveguide A). Furthermore, the pulsed light at λ_H **1122** can also enter either input port BSETin **1111** or BRESETin **1116** or output port ASETout **1114**

30 which doubles as a possible input port (not shown in FIG. 11). It should be further understood that the pulsed light at λ_{LL} **1124** can be input to the active

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medium **1108** on Waveguide A **1102** in any manner of implementation. For example, it can impinge on the active medium from outside the waveguides (e.g. from the top at a direction perpendicular to waveguide A). Furthermore, e.g., the pulsed light at λ_{LL} **1124** can also enter either input port BSETin **1111** or BRESETin **1116** or output port ASETout **1114** which doubles as a possible input port (not shown in FIG. 11). Preferably, the problem of any mixing of light that might occur is addressed by utilizing the dichroic filters **1126** and **1130**, in the exemplary manner illustrated in FIG. 11 or by using light of mutually orthogonal polarization with use of a polarization dependent beam splitter of coupler.

The exemplary embodiments **700** and **750** of exemplary device 3, illustrated in FIGS. 8A and 8B, respectively, were discussed above with reference to the way in which the devices **700, 750** could be switched between two states, the first state corresponding to Case "D" of FIG. 4D, and the second state corresponding to Case "C" of FIG. 4C. In the case of Phosistor **1100**, manipulating the intensity I_L of the pulsed light at λ_L **1118** can create an additional operational state corresponding to Case "A" of FIG. 4A. This operational state is exploited in Phosistor **1100**.

In a preferred embodiment, the Phosistor **1100** operates as a flip-flop according to restrictions that are placed on the relative magnitudes of the operating wavelengths λ_L, λ_H, and λ_{LL} of the light inputs **1118, 1122,** and **1124**, respectively. First, the pulsed light at λ_H **1122** (i.e., the "set" beam) has a wavelength λ_H that is shorter than or equal to the wavelength λ_L of the pulsed light at λ_L **1118** (the "enable" beam), that is, $\lambda_H \le \lambda_L$. Second, the pulsed light at λ_{LL} **1124** (i.e., the "reset" beam) has a wavelength that is longer than the wavelength λ_L of the pulsed light at λ_L **1118** as well as the pulsed light at λ_H, that is, $\lambda_{LL} > \lambda_L \ge \lambda_H$.

The former restriction ($\lambda_H \le \lambda_L$) for the exemplary embodiment of Phosistor **1100** has implications with regard to the two general wavelengths λ_1 and λ_2, where λ_1 has the longer wavelength as defined above with reference

to exemplary devices 1-4. As such, the Phosistor **1100** can operate with $\lambda_L =$
$\lambda_H = \lambda_1$, or $\lambda_L = \lambda_H = \lambda_2$, or $\lambda_L = \lambda_1$ and $\lambda_H = \lambda_2$.

i).   The Enable State

For this Enable state of Phosistor **1100**, the enable beam at λ_L **1118** is
turned "on," while the set beam at λ_H **1122** and the reset beam at λ_{LL} **1124** are
both "off."

To create the first operational state of the Phosistor Flip-Flop **1100** the
pulsed light at λ_L **1118** (the "enable" beam) is turned "on" and is maintained at
relatively low intensity so that the active medium **1108** on Waveguide A **1102**
will not be driven to transparency at λ_L. The intensity I_L of the light at λ_L **1118**
is kept purposely low enough so that $I_L < (1 / \eta) I_{LSat}$, that is, the intensity I_L
does not exceed the saturation intensity divided by η, the effective
percentage of leakage power to the active medium **1108** needed to bring the
active medium to the state of transparency when there is no set beam at λ_H
1122 entering the port ASETin **1106**. The enable beam at λ_L **1118** does not
have a high enough intensity to drive the active medium **1108** in Waveguide A
1102 to transparency at λ_L by itself. In this situation, most of the power of the
light beam at λ_L will exit port BRESETout **1112**.

In this case, the active medium **1108** provides loss at λ_L **1118**.
Essentially, the net result is that more electrons in the active medium **1108**
relax from high energy states (i.e. spontaneously decay) than are excited to
high energy states. This state of the active medium **1108** is analogous to
Case A, as illustrated in FIG. 4A.

ii).   The Set State

For this Set state of Phosistor **1100**, the enable beam at λ_L **1118** is
"on," the set beam at λ_H **1122** is turned "on," and the reset beam at λ_{LL} **1124**
remains "off." Once the set beam at λ_H **1122** is turned "on," the Phosistor

1100 is "latched" and remains in the Set state, even if the set beam at λ_H **1122** is turned "off," while the enable beam at λ_L **1118** is "on" and until the Phosistor **1100** is "reset."

By itself, the enable beam at λ_L **1118** does not have a high enough intensity to drive the active medium **1108** in Waveguide A **1102** to transparency at λ_L. By design, the enable beam at λ_L **1118** requires the assistance of the set beam at λ_H **1122** entering the port ASETin **1106** on dichroic filter **1126** to drive the active medium **1108** to transparency at λ_L. The set beam at λ_H **1122** preferably has a wavelength λ_H that is shorter than or equal to λ_L as described above.

The set beam at λ_H **1122** turns on and consequently drives the active medium **1108** to a state of transparency at λ_L. Preferably, part of the power of the enable beam at λ_L **1118** now splits to propagate through the active medium **1108** along the Waveguide A **1102** and subsequently exits from Waveguide A **1102** at the port ASETout **1114** as light at λ_L **1120**. This state of the active medium **1108** is analogous to Case D, as illustrated in FIG. 4D.

In effect, the set beam at λ_H **1122** latches the Phosistor **1100** flip-flop so that the active medium **1108** remains in a state of transparency at λ_L, even when the set beam at λ_H **1122** is turned off and is no longer present. That is, the enable beam at λ_L **1118** is purposely maintained at an intensity I_L that is too low to drive the medium **1108** to transparency at λ_L by itself, but the additional power latched to propagate through the active medium **1108** by the set beam at λ_H **1122** is sufficient to maintain the transparency at λ_L once the set beam at λ_H **1122** is turned off and is no longer present.

iii). The Reset State (Enable=1; Set=0; Reset=0→1→0)

For this Reset state of Phosistor **1100**, the enable beam at λ_L **1118** is "on," the set beam at λ_H **1122** is turned "off," and the reset beam at λ_{LL} **1124** is turned "on." Once the reset beam at λ_{LL} **1124** is turned "on," the Phosistor

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1100 is "unlatched" or "reset." When the reset beam at λ_{LL} **1124** is turned "off," the Phosistor **1100** returns to the Enable state, while the enable beam at λ_L **1118** is "on."

The reset beam at λ_{LL} **1124** entering the port BRESETin **1116** on dichroic filter **1130** will be coupled from Waveguide B **1104** to Waveguide A **1102** and will reach the active medium **1108** in Waveguide A and will de-excite or relax the active medium **1108** on Waveguide A **1102**, providing loss at the operating wavelength λ_L to the active medium **1108**. This state of the active medium **1108** is analogous to Case C, as illustrated in FIG. 4C.

The enable beam at λ_L **1118** from input port AENABLEin **1110** loses energy in the active medium **1108** so that **most of** the pulsed light at λ_L **1118** does not propagate all the way through the active medium and thus does not exit from the output port ASETout **1114** on Waveguide A **1102**. Rather, most of the pulsed light at λ_L **1118** propagates through Waveguide A **1102** along the interaction length ℓ and couples or transfers to Waveguide B **1104** and exits out of output port BRESETout **1114** as pulsed light at λ_L **1128** out of the Waveguide B **1104**.

In the case of FIG. 11, the net effect is that once the Phosistor **1100** is enabled by the enable beam at λ_L **1118**, application of a pulse of light at λ_H **1122** (the set beam) into port ASETin **1106** generates light at λ_L **1120** exiting port ASETout **1114**. The Phosistor **1100** will remain latched in this set state until the application of a reset pulse of light at λ_{LL} **1124**, which in turn generates a light at λ_L **1128** exiting port BRESETout **1112**.

It should be understood that in accordance with standard logical operation of Set-Reset flip-flops, the Phosistor **1100** when utilized as a flip-flop, preferably, simultaneous application of set and reset pulses of light **1122**, **1124**, respectively, should be avoided.

It should be understood that in the typical operation of the Phosistors, including the useful embodiment **1100**, one or more light inputs and outputs are described as pulsed light. This light can otherwise take the form of

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continuous wave (CW) light in some specific applications. For the purpose of illustration and not limitation, it is taken as pulsed light.

Since the active medium **1108** of device **1100** of FIG. 11 is operated at the absorbing or loss mode, this phosistor has a "loss gate". This gate is in the input arm (Waveguide A **1102**).

iv). MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator configuration for device 6 would be topologically similar to the MMI/ Resonator configuration of Device 1. As in device 1, it should be understood that the MMI/Resonator Configuration Devices are otherwise functionally and operationally identical to the device **1100** and descriptions and comments relating to the device **1100** are generally applicable to the MMI/Resonator Configuration Devices.

v). PBG Implementation of the Coupler/MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 6 would be topologically similar to the PBG implementations for the Coupler/MMI/Resonator configuration of device 1. As in device 1, it should be understood that the PBG implementations for the Coupler/MMI/Resonator configuration of device 6 are otherwise functionally and operationally identical to the device **1100** and descriptions and comments relating to the device **1100** are generally applicable to the PBG implementations for the Coupler/MMI/Resonator configuration of device 6.

G. EXEMPLARY DEVICE 7: AN OPTICAL AMPLIFIER

For purposes of illustration and not limitation, an Optical Amplifier can be constructed and implemented with the exemplary devices 1 and 2 cascaded together.

For example, FIG. 12 illustrates a seventh general embodiment **1200** of a phosistor device employing directionally coupled waveguides. The device can operate as an optical amplifier by management of, including optional switching of, streams of slow or ultrafast (picosecond, femtosecond) optical pulses of equivalent, comparable, or differing energies and wavelengths. The device in this exemplary embodiment **1100** can be referred to as an "Optical Amplifier Phosistor."

Optical Amplifier Phosistor **1200** shown in FIG. 12 preferably includes a first stage **1202** based on exemplary device 1 **550** (described above and shown in FIG. 6B) cascaded with a second stage **1204** based on exemplary device 2 **600** (described above and shown in FIG. 7). Those skilled in the art will appreciate that the detailed workings of the first and second stages **1202**, **1204** can be understood by with reference to the detailed descriptions provided for the exemplary embodiments **550** and **600** of exemplary devices 1 and 2, respectively. For clarity the signals presented to and output from the first and second stages **1202, 1204** of the Phosistor **1200** are described using consistent nomenclature to that used to describe the exemplary embodiments **550** and **600** of exemplary devices 1 and 2, respectively.

An amplifier input port **1208** of Optical Amplifier Phosistor **1200** is configured to receive continuous wave (CW) light at wavelength λ_1 (CW PWR IN λ_1) **1206**. Another input port **1210** of Phosistor **1200** is configured to receive pulsed light at wavelength λ_2 (SIGNAL IN λ_2) **1212**. An output port **1216** for exiting CW light at wavelength λ_1 (CW PWR BYPASS OUT λ_1) **1214** is included on Phosistor **1200**. Preferably, ports **1208, 1210**, and **1216** all service the first stage **1202** of the Optical Amplifier Phosistor **1200**.

An amplifier input port **1218** of Optical Amplifier Phosistor **1200** is configured to receive continuous wave (CW) light at wavelength λ_2 (CW PWR IN λ_2) **1220**. An output port **1224** for exiting pulsed light at wavelength λ_2

(SIGNAL IN λ_2) **1222** and another output port **1226** for exiting pulsed light at wavelength λ_2 (NEG SIG OUT λ_2) **1228** are included on Phosistor **1200**. Preferably, ports **1218, 1224,** and **1226** all service the second stage **1202** of the Optical Amplifier Phosistor **1200**.

Internal input and output ports **1232, 1234** are included in Phosistor **1200** to interface between the first and second stages **1202, 1204** of the Phosistor **1200**. Pulsed light at wavelength λ_1 (SIGNAL OUT λ_1/ SIGNAL IN λ_1/) **1230** exits from port **1232** and enters port **1234**.

i).   The First Stage (Exemplary Device 1)

CW light at λ_1 **1206** enters the first stage **1202** (exemplary device 1 **550**) of Phosistor **1200** via the port **1208**, drives the active medium internal to the first stage **1202** to transparency at λ_1 (Case C in FIG. 4C), and subsequently transfers via directionally coupled waveguides to the port **1216**, exiting as CW light at λ_1 **1214**. Application of pulsed light at λ_2 **1212** excites and provides gain at λ_1 to the active medium (Case B in FIG. 4B), generating pulsed light at λ_1 **1230**, exiting from the port **1232**. In certain exemplary embodiments of the device **550**, the CW light at λ_1 **1214** exiting the port **1216** is not substantially affected by the pulsed light at λ_2 **1212** so that the CW light at λ_1 **1214** can be used to power another Phosistor. Turning off the light at λ_2 **1212** allows the active medium to be driven back to a state of transparency at λ_1 (Case C in FIG. 4C) and light at λ_1 **1230** no longer exits from the port **1232**.

ii).   The Second Stage (Exemplary Device 2)

CW light at λ_2 **1220** enters the second stage **1204** (exemplary device 2 **600**) of Phosistor **1200** via the port **1218**, drives the active medium internal to the first stage **1202** to transparency at λ_2 (Case D in FIG. 4D), and subsequently transfers via directionally coupled waveguides to the port **1226**, exiting as light at λ_2 **1228**. Application of pulsed light at λ_1 **1230** (from the first

stage **1202**) de-excites and provides loss at λ_2 to the active medium (Case C-in FIG. 4C), so that at least a part of the CW light power at λ_2 **1220** does not transfer via the directionally coupled waveguides to the port **1226** but rather exits from the port **1224** as light at λ_2 **1222**. In certain exemplary embodiments of the device **600**, the device **600** is capable of providing photon gain, that is, a number X of photons at λ_1 (pulsed light at λ_1 **1230**) into the port **1234** results in a number Y of photons at λ_2 (light at λ_2 **1222**) out of the port **1224** where the number Y is capable of being greater than the number X.

Turning off the light at λ_1 **1230** allows the active medium to be driven back to a state of transparency at λ_2 (Case C in FIG. 4C) and light at λ_2 **1222** no longer exits from the port **1224**.

In summary, the first stage **1202** (exemplary device 1 **550**) of Phosistor **1200** shown in FIG. 12 translates the signal beam at λ_2 **1212** to the signal beam at λ_1 **1230**. The second stage **1204** (exemplary device 2 **600**), cascaded together in Phosistor **1200** with the first stage **1202**, translates the signal beam at λ_1 **1230** to the signal beam at λ_2 **1222** with amplification of the photon number. The net result is that first and second stages **1202, 1204** cascaded together as Phosistor **1200** realize an optical amplifier where the output optical signal, signal beam at λ_2 **1222**, has an increased number of photons relative to the input optical signal, signal beam at λ_2 **1212**. The increased number of photons on the output represents amplification of the input optical signal.

In an exemplary embodiment of Optical Amplifier Phosistor **1200**, the waveguide structures connecting and including the first and second stages **1202, 1204** can be implemented as the Waveguide **400** illustrated in FIG. 5A, in an $Al_xGa_{1-x}As$ embodiment having alloy composition x = 0.3 giving a bandgap energy of around 690nm. In an exemplary embodiment, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. In an exemplary embodiment of device **1200**, the waveguide structures

of FIG. 12 are 0.4 μm wide and are located at approximately parallel

distances from each other over coupling and interaction ranges of 0.4 μm.

It should be understood that these dimensions and exemplary lengths

are presented for purposes of illustrating a useful embodiment of the device

5   **1200** and are not intended to limit other exemplary embodiments of any

exemplary device, or the device **1200**. A variety of dimensions and sizes can

be used, depending on the application desired as well as the fabrication

materials, processes or technologies that are employed. Also, it should be

understood that the shape of the waveguides does not generally have to be

10   linear. Curved shapes and different waveguide dimensions may be utilized as

long as they achieve the same functions such as waveguiding and wave-

coupling. Furthermore, waveguides that are placed side by side to achieve

wave-coupling do not have to be placed side by side in a horizontal manner

but can be placed in a top-down vertical manner or any other manner with

15   respect to the horizontal substrate. Also coupled waveguides do not have to

be exactly parallel or have the same widths and dimensions as long as the

desired effect of wave-coupling is achieved.

It will be understood by those skilled in the art that the particular

operating details of the first and second stages **1202, 1204** beyond those

20   described above can be explained with reference to the detailed descriptions

provided for the exemplary embodiments **550** and **600** of exemplary devices 1

and 2, respectively.

It will be understood by those skilled in the art that the first and second

stages **1202, 1204** can be in other forms or configurations such as the MMI or

25   resonator configuration or other forms of implementation such as the photonic

bandgap or metallic waveguide implementation.

VI.   ELECTRO-OPTIC DEVICES

The presently preferred electro-optic phosistor embodiments and devices may be classified by such exemplary features as whether they manipulate the intensity levels of light signals, the functions performed by and unique to particular devices, and the state or states of the active medium that

5   drive the operation of the device. In most cases under discussion, light having wavelength λ_n preferably is input to the electro-optic phosistor either (1) in a continuous fashion with respect to time, that is, as continuous wave (CW) light having wavelength λ_n or (2) in a switched, or pulsed fashion with respect to time, so that pulsed light having wavelength λ_n is present for the duration of

10   the pulse, and is not substantially present otherwise (at least not at wavelength λ_n). Such a characterization of light will be familiar to those skilled in the art. Hereafter, for simplicity of description, light or another entity "having wavelength λ_n" can be referred to as being "at λ_n."

It should be understood that in the typical operation of the Electro-Optic

15   Phosistors, including the useful embodiments described below, one or more light inputs or outputs will be described as continuous wave (CW) light. This light can otherwise take the form of pulsed light in some specific applications. It is for the purposes of illustration and not limitation that one or more light inputs or outputs will be described as continuous wave (CW) light.

20   These electro-optic phosistors are also classified by their physical principles of operation. Like a transistor, an electro-optic phosistor can have three or more "terminals". An electro-optic phosistor can involve a wave-coupling junction such as a directional coupler, or a multi-mode interference (MMI) device or a resonator device or a photonic bandgap structure. There

25   are many ways to achieve a wave-coupling effect. One way is through coupled waveguides. Another way is through a multi-mode interference (MMI) device. There are also numerous ways to confine waves. One way is through a waveguide, another way is through a photonic bandgap device, and yet another way is through a metal coated or a metallic waveguide.

30   Regardless, it should be understood that the electro-optic phosistor devices and exemplary embodiments described herein use a combination of means to

resist or enhance the flow of photon flux in a certain direction by preferably altering the interference flux pattern of light via the action of an applied voltage on the medium. Preferably, the interference flux pattern of light identifies, and the light transfer control property of the active medium

5   determines, the propagation direction of the flow of photon flux in the electro-optic phosistor (photon transistor) at a given time.

A coupler device as herein described preferably transfers energy from one material region to another via interference. This interference causes the propagation direction of an input photon beam to deviate from straight line

10   propagation. In an electro-optic phosistor, this path-changing interference is interrupted in the coupler due to an absorbing or a gain medium controlled by an applied voltage, which leads to an effective "transfer photon-resistance" for the spatial propagation of the original photon beam resulting in an enhancement or reduction in the resultant energy flux in certain regions of the

15   coupler.

Presented herein are presently preferred and useful embodiments of electro-optic phosistor devices utilizing directional coupled waveguides in the form of waveguide **400** of FIG. 5A or waveguide **450** of FIG. 5D. In some instances one or more arms of the directionally coupled waveguides will have

20   an active region or medium in the form of active medium **420** (see FIG. 5D). In some instances, resonator configurations are used to reduce the operating voltages or currents.

It should be understood that other waveguides, besides conventional waveguides with high refractive index core surrounded by low refractive index

25   cladding such as waveguide **450**, can be utilized in electro-optic phosistor embodiments including other types of waveguiding devices such as those based on repeated reflection via metal surface structures or photonic-bandgap structures.

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VII.   ADDITIONAL EXEMPLARY DEVICES AND EMBODIMENTS

A.   EXEMPLARY DEVICE 8 (ELECTRO-OPTIC)

FIG. 13 illustrates an eighth exemplary device and a first general

5   embodiment **1500** of an electro-optic phosistor device employing directionally coupled waveguides. For purposes of illustration and not limitation, the device is described according to one useful function as a switching element for slow or ultrafast optical pulses of sufficient energy and wavelength. The device **1500** is not limited to use as a switching element and can be utilized,

10   for example, as a photon duplicator, a light intensity modulator, a light intensity regulator, a lossless signal tap, a quantum-nondemolition (QND) detector, and a variable optical attenuator. It should be understood that these exemplary applications of device **1500** are intended to illustrate the wide range of uses for device **1500**, and are not intended to limit the applications of

15   other exemplary embodiments of device **1500** to these examples. The device can be referred to as an "Electro-Optic Input-Arm-Gain-Loss Gate Phosistor" (EO IGL Phosistor **1500**).

EO IGL Phosistor **1500** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **1502** and a second

20   pathway of light consisting of the spatial region occupied by Waveguide B **1504**. The Waveguide A **1502** preferably includes an active medium **1508**. A Voltage Source **1506** having a variable voltage V is applied across the active medium **1508**. As described above, Waveguide A **1502** can be implemented as waveguide **450** illustrated in FIG. 5D with active medium **420** and

25   Waveguide B **1504** can be implemented as Waveguide **400** illustrated in FIG. 5A in a useful embodiment. The Waveguide A **1502** preferably includes an input port A1 **1510** and an output port A2 **1512**. The Waveguide B **1504** preferably includes an output port B2 **1514**. FIG. 13 illustrates that Waveguide A **1502** has width W_A and is located at an approximately parallel

30   distance (coupling gap or distance) W_g from Waveguide B **1504**, which has width W_B.

The input port A1 **1510** on the Waveguide A **1502** is configured to receive light having wavelength λ (at λ) (SIGNAL IN λ) **1518**. In a useful embodiment, this light at λ **1518** is continuous wave (CW) light. Depending on the state of the electro-optic phosistor **1500**, light can be output from the output port B2 **1514** as light having wavelength λ (at λ) (SIGNAL BYPASS OUT λ) **1520**. In a useful embodiment, this light at λ **1520** is continuous wave (CW) light. Light is also capable of being output from the output port A2 **1512** as light having wavelength λ (at λ) (SIGNAL OUT λ) **1516**. In a useful embodiment, this light at λ **1516** is pulsed light. Under certain condition described below when the active medium on the waveguide reaches transparency and Waveguides A and B are optically transparent, most of the CW light at λ **1518** propagating along the Waveguide A **1502** will be transferred to Waveguide B **1504** after a coupling length ℓ_c. It should be understood that the light signals into and out of IGL Phosistor **1500** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

The coupling length $\ell_c|_{x-y}$ is defined as the length at which a wave in a first waveguide (X) maximally couples into a second waveguide (Y) that is coupled to the first waveguide (X). In this device **1500**, the interaction length ℓ, defined as the length of interaction between waves in Waveguides A **1502** and B **1504** extends to approximately the full coupling length ℓ_c so that $\ell = \ell_c$ in one embodiment of the device. In the case of FIG. 13, the interaction length is defined geometrically by the length for which waveguides A and B run closely parallel to each other. In other exemplary devices, the interaction length could be chosen to be multiple odd numbers of the coupling length ℓ_c ($\ell = 3\ell_c, 5\ell_c, 7\ell_c...$). As is known to those skilled in the art, these coupling lengths will also achieve maximal coupling as for the case where $\ell = \ell_c$. While the choice of $\ell = \ell_c$ is illustrated in this exemplary device, the

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interaction length may vary from the coupling length ℓ_c (or multiple odd numbers of ℓ_c) without affecting the general operating principle of the device.

As shown in FIG. 13, the length L of the active medium **1508** is about half the interaction length ℓ ($L \cong \dfrac{\ell}{2}$). The length L of the active medium **1508** may be somewhat longer or shorter than half of ℓ. Varying the length L of the active medium **1508** relative to the interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **1500** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1500**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell = \ell_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ_c and still achieve similar device functions.

Also, it should be understood that the shape of the waveguides does not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an alternative location along waveguide B other than that illustrated in FIG. 13, and there can be more than one disconnected active medium areas along waveguide B. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel or have the same widths as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of device **1500** for operation at 800nm wavelength range, the wavelength λ can be at 820nm and the Waveguide A **1502** can be implemented as the Waveguide **450** with an active medium **420** illustrated in FIG. 5D and Waveguide B **1504** can be implemented as the Waveguide **400** illustrated in FIG. 5A, in an $Al_xGa_{1-x}As$ embodiment for the waveguide core having alloy composition x =0.3, giving a bandgap energy of around 690nm. Thus the core material in waveguides A and B is transparent at the wavelength λ of 820nm. When the active medium in waveguide A is fully de-excited, the active medium absorbs light at 820nm wavelength. The active medium is an essentially three-level medium for which the electrons supplied from current injection are free to relax from an upper-energy level to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of device **1500** for operation at 1500nm wavelength range, the wavelength λ can be at 1500nm and the Waveguide A **1502** can be implemented as the Waveguide **450** with an active medium **420** illustrated in FIG. 5D and Waveguide B **1504** can be implemented as the Waveguide **400** illustrated in FIG. 5A, in an $In_{1-x}Ga_xAs_{1-y}P_y$ embodiment for the waveguide core having alloy compositions x=0.16 and y=0.67, giving a bandgap energy of around 1100 nm. Thus the core material in waveguides A and B is transparent at the wavelength λ of 1500nm. When the active medium in waveguide A is fully de-excited, the active medium absorbs light at 1500nm wavelength. The active medium is an essentially three-level medium for which the electrons supplied from current injection are free to relax from an upper-energy level to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for application to the 1500nm (or 1.5 μm) wavelength range, the cross-sectional dimensions of the waveguide **400** or **450** are 0.4 μm wide by 0.25 μm thick. In this exemplary embodiment, the Waveguide A **1502** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_g from Waveguide B **1504** of 0.4 μm, while Waveguide B **1504** has width W_B equal to 0.4 μm. The material refractive

indices of the Waveguides A, the Waveguide G, and the Waveguide B are denoted as n_A, n_B, and n_C, respectively, and are taken to be $n_A=n_B=n_G=3.4$. These refractive indices give an effective planar-waveguide propagating refractive index of about 2 in a planar waveguide structure with a thickness of

5   0.25 μm. The material refractive index outside the waveguides is taken to be 1.5, which will be the case if the material outside the waveguide is silicon dioxide. In this exemplary embodiment for which the wavelengths of light are at around 1500nm range, ℓ_c is about 15 μm.

It should be understood that these dimensions, exemplary lengths, and

10   geometry are presented for purposes of illustrating a useful embodiment of the devices **1500** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **1500**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

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i).   General Operation of the Device

The main action of the injection current or applied voltage to the active medium preferably is to bring the medium from a state of loss or transparency

20   to a state of gain. The loss, transparency, or gain state of the medium then affects the transfer of light from various inputs to various outputs. The general operation of the device can be illustrated via computer simulation of such light transfer as a function of the medium's loss/gain coefficient (gain and loss coefficients are related as loss coefficient can be described as a negative gain

25   coefficient).

An exemplary operation of the device can be illustrated via the result of computer simulation as shown in FIGs. 13A, 13B, 13C, and 13D for operation at 1500nm wavelength range. The geometry for the device simulated is as described by the exemplary embodiment given above for application to the

30   1500nm wavelength range. For this simulation, the active medium 420 is assumed to have a full-excitation gain coefficient of about 1 per μm, and ℓ_c is

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15 μm. FIGs. 13A, 13B, and 13C show the spatial distribution of the electric field strength for the light input at λ**1518** after propagating into waveguides A and B. The upper parts of FIGs. 13A, 13B, and 13C are 2-D plots for which the brightness shows the relative field strength, and the lower parts of FIGs. 13A, 13B, and 13C are 3-D plots for which the heights show the relative field strength. FIG. 13D shows the relative power at the output ports of waveguide A (port A2) and waveguide B (port B2) as a function of -gL (negative of the product between the gain coefficient g and the medium length L). In the figure, the output at A2 is shown as dotted line, the output at B2 is shown as a dashed line, and the solid line is the sum of the outputs at A2 and B2 (i.e. the dashed line plus the dotted line). In FIG 13D, negative gL means the medium is in a state of loss. FIG. 13A shows the situation when the gain medium is in the state of loss or transparency (at a gain coefficient of 0 per μm or gL=0). From FIG. 13A, it is evident that most of the energy of λ**1518** exits from Waveguide B **1504** at the port B2 **1514**. FIG. 13B shows the situation when the medium is excited to the critical gain value (at a gain coefficient of about 0.4 per μm or a gL=3.0) by the injection current. From FIG. 13B it is evident that approximately an equal amount of energy of λ exits from Waveguide A and Waveguide B and the energy exiting waveguide B is not substantially affected (it increases by at most a factor of two). FIG. 13C shows the situation when the medium is excited above the critical gain value (at a gain coefficient of about 1 per μm or a gL=7.5) for which the energy exiting waveguides A and B are increased substantially from their values of FIG. 13A. From figure 13D, we see that a good operating point is just above the critical value for which the energy exiting waveguide A is much more than the energy exiting waveguide B, which means the gain medium is transferring most of its energy to output A2 at waveguide A, thereby achieving high energy conversion efficiency.

We note that FIG. 13A and FIG. 13B in particular, show the two representative interference flux patterns of light for the device, which is dependent on the state of the active medium. One can switch between these two representative interference flux patterns of light by changing the state of

the active medium through the action of an applied voltage or injection current.

ii). Exemplary Device States

5   Various operating modes of a general active region or medium (such as active medium **420** operating as a PN or PIN junction) with an applied voltage V (or injection current C) were defined and described above and illustrated in FIG. 4G-K. Since the electro-optic phosistors such as device **1500** and related exemplary embodiments thereto preferably include one or

10   more active regions, the devices and embodiments thereto can be characterized according to the states illustrated in FIG. 4G-K.

In a preferred and useful embodiment, the electro-optic phosistor **1500** operates as a switching element. The wavelength of the light at λ input to the device **1500** is preferably around the bandgap energy (associated with λ_{gap}).

15   It should be understood that the light signals into and out of IGL Phosistor **1500** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

20   It should be understood that the action of the exemplary Phosistor **1500** is defined by the paths taken by the light beams in the device **1500**. The paths taken by the light beams in the device **1500** are preferably dependent on the state of the active medium in the interaction region of the Phosistor **1500** (e.g. state of loss, transparency, or gain).

25   The combination of the state of the active medium and the state of light beam propagation in the device define the state of the device. The various operations of the device **1500** can be more precisely described in terms of such device states. It should be understood however that more or fewer device states can be applied to and described instructively with respect to

30   device **1500** in this or in other useful embodiments and/or applications.

In particular, the operation of the device can be described as making transitions from one class of states to another class of states under the

influence of some external inputs such as the power of the input beam, the locations where the input beam is received, and applied electrical energy, preferably including applied voltages or currents.

iii).   A First Exemplary Device State

For this first exemplary device state of the electro-optic phosistor **1500**, the light beam at λ **1518** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1518** can be greater than, equal to, or less than the saturation intensity I_{sat} of the active medium **1508**. The voltage V of the variable voltage source **1506** that is applied across the PN or PIN junction (where "I" refers to intrinsic semiconductor that may include quantum wells), including the active medium **1508**, is less than approximately zero volts (i.e., $V<0$ volts). The state of the active medium is analogous to State K as illustrated in FIG. 4K. At this value, the PN or PIN junction including the active medium **1508** is reverse-biased by the applied voltage V.

Light at λ **1518** enters at the port A1 **1510** on the Waveguide A **1502**. The light at λ **1518** propagates along the Waveguide A **1502** and most of the light at λ **1518** is subsequently transferred to Waveguide B **1504** after a coupling length ℓ_c. Most of the light at λ **1518** then exits from Waveguide B **1504** at the port B2 **1514** as light at λ **1520**. The active medium **1508** is in a state of loss at λ and maintains this state while the applied voltage V is below approximately zero volts.

iv).   A Second Exemplary Device State

For this second exemplary device state of the electro-optic phosistor 1500, the light beam at λ **1518** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1518** can be either greater than, equal to or less than the saturation intensity I_{sat} of the active medium **1508**. The voltage V of the variable voltage source **1506** that is applied across the PN or PIN junction including the active medium **1508**, is approximately equal to the value of the voltage that is associated with a critical value of the injection current, $C_t(\lambda)$ (i.e., $V \cong V|_{c=C_t(\lambda)}$), called the transparency current. At this value, the PN or PIN junction including the active medium **1508** is forward-biased by the applied voltage V. This transparency current, $C_t(\lambda)$ is the approximate value of the current when the active medium **1508** is driven to a state of transparency at wavelength λ by the current. The corresponding voltage $V|_{c=C_t(\lambda)}$ that gives rise to this transparency current $C_t(\lambda)$, is called the transparency voltage. This state of the active medium is analogous to State H as illustrated in FIG. 4H.

Light at λ **1518** enters at the port A1 **1510** on the Waveguide A **1502**. The light at λ **1518** propagates along the Waveguide A **1502** and most of the light at λ **1518** is subsequently transferred to Waveguide B **1504** after a coupling length ℓ_c. Most of the light at λ **1518** then exits from Waveguide B **1504** at the port B2 **1514** as light at λ **1520**. The active medium **1508** is in a state of transparency at λ and maintains this state while the applied voltage V is approximately at the transparency voltage $V|_{c=C_t(\lambda)}$. Not enough electron excitations are supplied by the applied voltage/injection current to drive the active medium to a gain state at λ. This state of the active medium **1508** is analogous to State H, as illustrated in FIG. 4H.

v).   A Third Exemplary Device State

For this third exemplary device state of the electro-optic phosistor
1500, the light beam at λ **1518** is turned "on." The wavelength λ is at the
wavelength of absorption and gain of the active medium, which is slightly
shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The
intensity I_λ of the light beam at λ **1518** can be greater than, equal to, or less
than the saturation intensity I_{sat} of the active medium **1508**. The voltage V of
the variable voltage source **1506** that is applied across the PN or PIN junction
including the active medium **1508**, is greater than the value of the voltage
(transparency voltage) that is associated with the value of the transparency
injection current, C_t (i.e., $V > V\big|_{c=c_t(\lambda)}$).

As the applied voltage V of the variable voltage source **1506** increases
beyond the transparency voltage at $V = V\big|_{c=c_t(\lambda)}$ the applied voltage V will
excite the active medium **1508**, providing gain at the operating wavelength λ
to the active medium **1508** located in Waveguide A **1502**. This state of the
active medium **1508** is analogous to State J, as illustrated in FIG. 4J.

This state (State J of FIG. 4J) is characterized by a relatively fast
electron excitation due to the increased injection current C and applied
voltage V compared with the second exemplary device state of the exemplary
device (State H of FIG. 4H).

Part of the light at λ **1518** from input port A1 **1510** gains energy in the
active medium **1508** and this extra energy propagates towards and exits port
A2 **1512**. This state of the active medium **1508** is analogous to State J, as
illustrated in FIG. 4J.

It should be understood that, in an exemplary embodiment, the energy
exiting the port B2 **1514** on Waveguide B **1504** (as light at λ **1520**) can be
designed to be not substantially affected in this state. The energy exiting the

port B2 **1514** of the electro-optic phosistor **1500** of FIG. 13 is capable of being reused to supply signal or power input(s) to other electro-optic phosistors.

For this third exemplary device state, if the applied Voltage V is increased beyond a decoupling voltage V_{decouple} (i.e. $V > V_{decouple} > V\big|_{C=C_t}$), then

5   the gain at λ of the active medium **1508** will increase to a level such that the light at λ **1518** will no longer couple to or transfer to Waveguide B **1504** from Waveguide A **1505** without substantial change in power. Rather the light at λ **1516** exiting port A2 **1512** and port B2 **1514** will increase in intensity relative to the intensity of I_λ of the light at λ **1518**, due to the increased gain at λ of the

10   active medium **1508** on Waveguide A **1502**.

vi).   Transitions for the Active Medium States and Device States

Transition from one active medium state to another is brought about by

15   changing the applied voltage. The change in the active medium state then brings about a corresponding change in the device state, resulting in a change in the behavior of the light beams propagating through the device.

As an example of such transitions, suppose we start with a forward-biased voltage at above the transparency voltage $V > V\big|_{C=C_t(\lambda)}$. In this case,

20   the active medium **1508** is in the state of gain analogous to State J, as illustrated in FIG. 4J (the third exemplary device state of the exemplary device 8). The active medium **1508** when in the gain state at λ (State J in FIG. 4J) will be driven back to the transparency state at λ (State H in FIG. 4H) when the applied voltage V of the variable voltage source **1506** decreases to

25   become approximately equivalent to the transparency voltage at $V = V\big|_{C=C_t(\lambda)}$.

The state of the active medium **1508** is again analogous to State H, as illustrated in FIG. 4H (the second exemplary device state of the exemplary device 8). This state (State H of FIG. 4H) is characterized by a relatively low electron excitation compared with State J of FIG. 4J (the third exemplary

30   device state of the exemplary device 8).

When the voltage V is further reduced from $V\big|_{C=C_t(\lambda)}$ to zero and then

to a reverse bias (V<0), any excited electrons will be de-excited and the

medium will be driven to and will maintain a loss state. The state of the active

medium **1508** is again analogous to State K, as illustrated in FIG. 4K (the first

5   exemplary device state of the exemplary device 8).

vii).   Exemplary Device 8 as a Switching or Modulation Element

For a given light input at λ **1518**, in the case of device **1500** of FIG. 13,

10   the net effect of varying the voltage applied to the active medium **1508** is that

increasing the applied voltage V beyond the transparency voltage $V\big|_{C=C_t(\lambda)}$

generates light at λ **1516** exiting port A2 **1512**. Decreasing the applied

voltage V below $V\big|_{C=C_t(\lambda)}$ removes most of the light at λ **1516** exiting port A2

1512. In this way, the electro-optic phosistor **1500** can be used as a voltage-

15   controlled switching element between the second and third exemplary device

states described above.

As the number of electrons excited in the active medium **1508** is

approximately equal to the number of electrons from the injection current

flowing into the upper-energy level of the medium **1508**, so the number of

20   photons generated at λ and propagated toward the output port **1512** is

approximately equal to the number of electrons excited, if the photons are

generated at λ, before the free decay of the electrons which takes place on a

nanosecond time scale (for a semiconductor medium). This can occur at

beam intensity high enough for at the stimulated decay rate of the excited

25   electrons to exceed its spontaneous decay rate, such as with a beam intensity

higher than the saturation intensity of the medium ($I_\lambda > I_{Sat}$). As a result, the

number of photons out at λ would be nearly equal to (i.e. correlated to) the

number of electrons from the injection current if the majority of the electrons

ends up as excited electrons in the medium **1508**. This is called electron-photon quantum-number correlation. When this happens, the device **1500** can be used as a high or near unity quantum efficiency device. If the input signal light **1518** is a continuous wave (CW) beam, then the net action of the exemplary device **1500** is to translate a beam of electrons to a beam of photons. Hence, this device can act as a quantum-number correlated electron to photon converter. In particular, if the injection current is constant, the photon flux or light power exiting port A2 **1512** will be relatively constant. In this case, the device acts as a light power regulator.

It should be understood that this description covers several but not all aspects of device performance. For example, the light at λ ($\lambda \geq \lambda_{gap}$) can be on or off, and if the light at λ is on, the intensity I_λ of the light at λ can be greater than, equal to, or less than the saturation intensity of the active medium **1508**. In addition, the PN or PIN junction that preferably includes the active medium **1508** can be forward (approximately V>0) or reverse (approximately V<0) biased by the applied voltage V of the variable voltage source **1506**. The applied voltage V has an associated injection current C. As shown above, when V exceeds zero volts (approximately), the value of V relative to the transparency voltage at $C=C_t$ and the decoupling voltage $V_{decouple}$ has implications for the operation of the device **1500** and the state of the active medium **1508**. The active medium **1508** can exhibit loss, transparency, or gain at the wavelength of operation λ depending on the light intensity at λ, the wavelength λ, and the applied voltage V and/or injection current C. It should be understood, however, that more or fewer states of the active medium can be applied to and described instructively with respect to device **1500** in this or in other useful embodiments and/or applications.

In another useful embodiment of the device, the interaction length ℓ is shorter than the coupling length ℓ_c ($\ell < \ell_c$). In this case not all the signal power at λ from port A1 **1510** will be coupled from Waveguide A **1502** to Waveguide B **1504** even when the medium **1508** is at a transparency state as in state H of FIG. 4H. Preferably, part of the signal power at λ will propagate

through the active medium **1508** and exit out of port A2 **1512**. A reverse bias applied to the active medium as in state K of FIG. 4K will turn the medium to a loss state at λ and the signal light propagating into the active medium will be mostly absorbed and little signal power at λ will exit port A2 **1512**. In this way, the electro-optic phosistor **1500** can be used as a voltage controlled switching element between the first and second exemplary states described above and can act as an optical intensity modulator.

It should be understood that these dimensions and exemplary lengths are presented for purposes of illustrating a useful embodiment of the device **1500** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1500**. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

viii).   MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator I/Resonator II configuration for device 8 would be topologically similar to the MMI/Resonator configuration of Device 1. As in device 1, it should be understood that the MMI/Resonator I/Resonator II Configuration Devices are otherwise functionally and operationally identical to the device **1500** and descriptions and comments relating to the device **1500** are generally applicable to the MMI/Resonator Configuration Devices.

viiii).   PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator configuration of device 8 would be topologically similar to the PBG implementations for the Coupler/MMI/Resonator configuration of device 1. As in device 1, it should be understood that the PBG implementations for the Coupler/MMI/Resonator

configuration of device 8 are otherwise functionally and operationally identical to the device **1500** and descriptions and comments relating to the device **1500** are generally applicable to the PBG implementations for the Coupler/MMI/Resonator configuration of device 8.

As with previously described embodiments, it should be understood that the dimensions and materials for the devices are presented for purposes of illustrating a useful embodiment of the device **1500** and its MMI/PBG/Resonator versions, and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1500** its MMI/PBG/Resonator versions. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety of materials can be used, for example, the waveguides do not have to be semiconductor and may be optical fibers or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved), the active medium does not have to be a semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite gain/loss/transparency properties are achived), and the resonators do not have to be semiconductors but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the shape of the Waveguides, MMI Structures, Photonic Bandgap Structures, or Resonators does not generally have to be linear, circular, parallel, or regular in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

It should be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the refractive index of the active medium could occur when the active medium changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the working of these devices include those cases whereby both the

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gain/transparency/loss property as well as the refractive-index property of the active medium are used in bringing about the device operation.

B.   EXEMPLARY DEVICE 9 (ELECTRO-OPTIC)

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FIG. 14 illustrates a ninth exemplary device and a second general embodiment **1600** of an electro-optic phosistor device employing directionally coupled waveguides. For purposes of illustration and not limitation, the device is described according to one useful function as a switching element

10   for slow or ultrafast optical pulses of sufficient energy and wavelength. The device **1600** is not limited to use as a switching element for a single light input and can be utilized as, for example, as an M x N switch, a variable coupling device (including its use in an optical loop mirror and a pulse storage ring), an electro-optic phase shifter, a resonator frequency tuning element, a light

15   intensity modulator, a light intensity regulator, and a variable optical - attenuator. It should be understood that these exemplary applications of device **1600** are intended to illustrate the wide range of uses for device **1600**, and are not intended to limit the applications or other exemplary embodiments of device **1600** to these examples. The device can be referred to as an

20   "Electro-Optic Output-Arm-Gain-Loss Gate Phosistor" (EO OGL Phosistor **1600**).

EO OGL Phosistor **1600** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **1602** and a second pathway of light consisting of the spatial region occupied by Waveguide B

25   **1604**. The Waveguide B **1604** preferably includes an active medium **1608**. A Voltage Source **1606** having a variable voltage V is applied across the active medium **1608**. As described above, Waveguide B **1604** can be implemented as waveguide **450** illustrated in FIG. 5D with active medium **420** and Waveguide A **1602** can be implemented as Waveguide **400** illustrated in FIG.

30   5A in a useful embodiment. The Waveguide A **1602** preferably includes an input port A1 **1610** and an output port A2 **1612**. The Waveguide B **1604**

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preferably includes an output port B2 **1614**. FIG. 14 illustrates that Waveguide A **1602** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_g from Waveguide B **1604**, which has width W_B.

The input port A1 **1610** on the Waveguide A **1602** is configured to
5   receive light having wavelength λ (at λ) (SIGNAL IN λ) **1618**. In a useful embodiment, this light at λ **1618** is continuous wave (CW) light. Depending on the state of the electro-optic phosistor **1600**, light can be output from the output port B2 **1614** as light having wavelength λ (at λ) (ON-SIGNAL OUT λ) **1620**. In a useful embodiment, this light at λ **1620** is pulsed light. Light is also
10   capable of being output from the output port A2 **1612** as light having wavelength λ (at λ) (OFF-SIGNAL OUT λ) **1616**. In a useful embodiment, this light at λ **1616** is pulsed light. Under certain conditions described below when the active medium on the waveguide reaches transparency and Waveguides A and B are optically transparent, most of the CW light at λ **1618** propagating
15   along the Waveguide A **1602** will be transferred to Waveguide B **1604** after a coupling length ℓ_c. It should be understood that the light signals into and out of OGL Phosistor **1600** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular
20   application.

The coupling length $\ell_c|_{x-y}$ is defined as the length at which a wave in a first waveguide (X) maximally couples into a second waveguide (Y) that is coupled to the first waveguide (X). In this device **1600**, the interaction length ℓ, defined as the length of interaction between waves in Waveguides A **1602**
25   and B **1604** extends to approximately the full coupling length ℓ_c, so that $\ell = \ell_c$ in one useful embodiment of the device, but can be different from ℓ_c in other useful embodiments of the device. In the case of FIG. 14, the interaction length is defined geometrically by the length for which waveguides A and B run closely parallel to each other.

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As shown in FIG. 14, the length L of the active medium **1608** is equal to the interaction length ℓ $(L = \ell)$. The length L of the active medium **1608** may be longer or shorter than ℓ. Varying the length L of the active medium **1608** relative to the interaction length ℓ will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **1600** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1600**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell = \ell_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ_c and still achieve similar device functions.

Also, it should be understood that the shape of the waveguides does not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an alternative location along waveguide B other than that illustrated in FIG. 14, and there can be more than one disconnected active medium areas along waveguide B. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of device 1600 for operation at 800nm wavelength range, the wavelength λ can be at 820nm and the Waveguide A **1602** can be implemented as the Waveguide **400** illustrated in FIG. 5A and Waveguide B **1604** can be implemented as the Waveguide **450** with an active

medium **420** illustrated in FIG. 5D, in an $Al_xGa_{1-x}As$ embodiment for the waveguide core having alloy composition x =0.3 giving a bandgap energy of around 690nm. Thus the core material in waveguides A and B is transparent at the wavelength λ of 820nm. When the active medium in waveguide B is fully de-excited, the active medium absorbs light at 820nm wavelength. The active medium is an essentially three-level medium for which the electrons supplied from current injection are free to relax from an upper-energy level to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of device **1600** for operation at 1500nm wavelength range, the wavelength λ can be at 1500nm and the Waveguide A **1602** can be implemented as the Waveguide **400** illustrated in FIG. 5A and Waveguide B **1604** can be implemented as the Waveguide **450**. Both have an active medium **420** illustrated in FIG. 5D, in an $In_{1-x}Ga_xAs_{1-y}P_y$ embodiment for the waveguide core having alloy compositions x=0.16 and y=0.67 giving a bandgap energy of around 1100 nm. Thus the core material in waveguides A and B is transparent at the wavelength λ of 1500nm. When the active medium is fully de-excited, the active medium in waveguide B absorbs light at 1500nm wavelength. The active medium is an essentially three-level medium for which the electrons supplied from current injection are free to relax from the upper-energy level to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for application to the 1500nm (or 1.5 μm) wavelength range, the cross-sectional dimensions of the waveguide **400** or **450** are 0.4 μm wide by 0.25 μm thick. In this exemplary embodiment, the Waveguide A **1502** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_g from Waveguide B **1604** of 0.4 μm, while Waveguide B **1504** has width W_B equal to 0.4 μm. The material refractive indices of the Waveguides A, the Waveguide G, and the Waveguide B are denoted as n_A, n_B, and n_C, respectively, and are taken to be $n_A=n_B=n_G=3.4$. These refractive indices give an effective planar-waveguide propagating refractive index of about 2 in a planar waveguide structure with a thickness of

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0.25 μm. The material refractive index outside the waveguides is taken to be 1.5. In this exemplary embodiment for which the wavelengths of light are at around 1500nm range, ℓ_c is 15 μm.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **1600** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **1600**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i)   General Operating Principle for the Device

The main action of the injection current or applied voltage to the active medium preferably is to bring the medium from a state of loss or transparency to a state of gain. The loss, transparency, or gain state of the medium then affect the transfer of light from various inputs to various outputs. The general operation of the device can be illustrated via computer simulation of such light transfer as a function of the medium's loss/gain coefficient (gain and loss coefficients are related as loss coefficient can be described as negative gain coefficient).

An exemplary operation of the device can be illustrated via the results of computer simulation as shown in FIGs. 14A, 14B, and 14C for operation at 1500nm wavelength range. The geometry for the device simulated is as described by the exemplary embodiment given above for application to the 1500nm wavelength range. FIGs. 14A and 14B show the spatial distribution of the electric field strength for the light input at λ **1618** after propagating into waveguides A and B. The upper parts of FIGs. 14A and 14B are 2-D plots for which the brightness shows the relative field strength, and the lower parts of FIGs. 14A and 14B are 3-D plots for which the heights show the relative field strength. FIG. 14C shows the relative power at the output ports of waveguide A (port A2 **1612**) and waveguide B (port B2 **1614**) as a function of –gL (the product of the loss coefficient –g and the medium length L). In FIG. 14C, the

output at A2 is shown as a dotted line, the output at B2 is shown as a dashed line, and the solid line is the sum of the outputs at A2 and B2 (i.e. the dashed line plus the dotted line). FIG. 14A shows the situation when the gain medium is in the state of transparency (at a loss coefficient of 0 per μm or –gL=0).

5   From FIG. 14A, it is evident that most of the energy of λ **1618** exits from Waveguide B **1604** at the port B2 **1614**. FIG. 14B shows the situation when the medium is de-excited to the state of loss at λ (at a gain coefficient of about -3.3 per μm or –gL=50). From FIG. 14B, it is evident that most of the energy of λ exits from Waveguide A. FIG. 14A and FIG. 14B show the two

10   representative interference flux patterns of light for the device, which is dependent on the state of the active medium. In particular, one can switch between these two representative interference flux patterns of light by changing the state of the active medium through the action of an applied voltage or injection current. Note that besides these two states, there are

15   other states, for example the intermediate state at –gL=6 shown in FIG. 14C, for which there is substantial total energy absorbed by the loss medium so that both output ports at waveguide A and waveguide B have low output power.

FIG. 14D, depicts the case of a longer device for which the gap W_g is

20   1.2 μm instead of 0.4 μm, and the coupling length ℓ_c is 120 μm. Again the interaction length ℓ is set equal to ℓ_c and the medium length L is equal to ℓ_c. FIG. 14D shows the relative powers at the output ports of waveguide A (port A2) and waveguide B (port B2) as a function of gL (the product between the gain coefficient g and the medium length L). Comparing FIG. 14C and FIG

25   14D, we see that the switching is more complete for the longer device case of FIG. 14D. While switching still occurs at a gL of about -50, a longer L means a short g (for gL=-50, L=120 μm, we have g= -0.4/ μm), while means the switching voltage can be lower.

ii) Exemplary Device States

30   Various operating modes of a general active region or medium (such as active medium **420** operating as a PN or PIN junction) with an applied

voltage V (or injection current C) were defined and described above and illustrated in FIG. 4G-K. Since the electro-optic phosistors such as device **1600** and related exemplary embodiments thereto preferably include one or more active regions, the devices and embodiments thereto can be
5   characterized according to the states illustrated in FIG. 4G-K.

In a preferred and useful embodiment, the electro-optic phosistor **1600** operates as a switching element. The wavelength of the light at λ input to the device **1600** is preferably around the bandgap energy (associated with λ_{gap}).

It should be understood that the light signals into and out of OGL
10   Phosistor **1600** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

It should be understood that the action of the exemplary Phosistor
15   **1600** is defined by the paths taken by the light beams in the device **1600**. The paths taken by the light beams in the device **1600** are preferably dependent on the state of the active medium in the interaction region of the Phosistor **1600** (e.g. state of loss, transparency, or gain).

The combination of the state of the active medium and the state of light
20   beam propagation in the device define the state of the device. The various operations of the device **1600** can be more precisely described in terms of such device states. It should be understood however that more or fewer device states can be applied to and described instructively with respect to device **1600** in this or in other useful embodiments and/or applications.
25   In particular, the operation of the device can be described as making transitions from one class of states to another class of states under the influence of some external inputs such as the power of the input beam, the locations where the input beam is received, applied electrical energy preferably including applied voltages or currents.

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iii).   A First Exemplary Device State

For this first exemplary device state of the electro-optic phosistor **1600**, the light beam at λ **1618** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1618** can be greater than, equal to, or less than the saturation intensity I_{sat} of the active medium **1608**. The voltage V of the variable voltage source **1606** that is applied across the PN or PIN junction including the active medium **1608**, is approximately less than or equal to zero volts. At this value, the PN or PIN junction, including the active medium **1608**, is reverse-biased by the applied voltage V.

Light at λ **1618** enters at the port A1 **1610** on the Waveguide A **1602**. The light at λ **1618** propagates along the Waveguide A **1602**. The energy of light at λ **1618** that reaches waveguide B will lose energy in the active medium **1608** so that the most of the light at λ **1618** does not transfer to Waveguide B **1604** and thus does not exit from the output on B2 **1614**. Rather, most of the light at λ **1618** propagates through Waveguide A **1602**, and exits from Waveguide A **1602** at the port A2 **1612** as light at λ **1616**. The reverse bias from the applied voltage V drives the active medium **1608** to a state of loss at λ and maintains this state while the applied voltage V is approximately at or below zero volts. There is effectively little electron excitation. Instead there is fast electron de-excitation occurring to assist in driving the active medium to a loss state at λ. This state of the active medium **1608** is analogous to Case K, as illustrated in FIG. 4K.

iv).   A Second Exemplary Device State

For this second exemplary device state of the electro-optic phosistor **1600**, the light beam at λ **1618** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1618** can be greater than, equal to, or less

than the saturation intensity I_{sat} of the active medium **1608**. The voltage V of the variable voltage source **1606** that is applied across the PN or PIN junction including the active medium **1608**, is approximately equal to the value of the voltage that is associated with a critical value of the injection current, $C_t(\lambda)$

(i.e., $V \cong V\big|_{c=C_t(\lambda)}$), called the transparency current. At this value, the PN or PIN junction including the active medium **1608** is forward-biased by the applied voltage V. This transparency current, $C_t(\lambda)$ is the approximate value of the current when the active medium **1608** is driven to a state of transparency at wavelength λ by the current. The corresponding voltage $V\big|_{c=C_t(\lambda)}$ that gives rise to this transparency current $C_t(\lambda)$, is called the transparency voltage. This state of the active medium is analogous to State H as illustrated in FIG. 4H.

Light at λ **1618** enters at the port A1 **1610** on the Waveguide A **1602**. The light at λ **1618** propagates along the Waveguide A **1602** and is subsequently transferred to Waveguide B **1604** after a coupling length ℓ_c. The light at λ **1618** then exits from Waveguide B **1604** at the port B2 **1614** as light at λ **1620**. While the applied voltage V is approximately at the transparency voltage $V\big|_{c=C_t(\lambda)}$, the active medium **1608** is driven to and maintained in a state of transparency at λ. Not enough electron excitations are supplied by the applied voltage/injection current to drive the active medium to a gain state at λ. This state of the active medium **1608** is analogous to Case H, as illustrated in FIG. 4H.

v). A Third Exemplary Device State

For this third exemplary device state of the electro-optic phosistor **1600**, the light beam at λ **1618** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1618** is either greater than, equal to, or less than the saturation intensity I_{sat} of the active medium **1608**. The voltage V of

the variable voltage source **1606** that is applied across the PN or PIN junction including the active medium **1608**, is greater than the value of the voltage that is associated with the transparency value of the injection current, C_t (λ) (i.e., $V > V\big|_{C=C_t(\lambda)}$).

As the applied voltage V of the variable voltage source **1606** increases beyond the transparency voltage at $V = V\big|_{C=C_t(\lambda)}$, the applied voltage V will excite the active medium **1608**, providing gain at the operating wavelength λ to the active medium **1608** located in Waveguide B **1604**. This state of the active medium **1608** is analogous to Case J, as illustrated in FIG. 4J.

This state (state J of FIG. 4J) is characterized by a relatively fast electron excitation due to the increased injection current C and applied voltage V compared with the first exemplary state of the exemplary device (state H of FIG. 4H).

Some of the light at λ **1618** from input port A1 **1610** transfers to Waveguide B **1604** and gains energy in the active medium **1608** and some extra energy does not exit Waveguide B **1604** but rather propagates towards and exits port A2 **1612**.

vi).   Transitions for the Active Medium States and Device States

Transition from one active medium state to another is brought about by changing the applied voltage. The change in the active medium state then brings about a corresponding change in the device state, resulting in a change in the behavior of the light beams propagating through the device.

As an example of such transitions, suppose we start with a forward-biased voltage at above the transparency voltage $V > V\big|_{C=C_t(\lambda)}$. In this case, the active medium **1608** is in the state of gain analogous to State J, as illustrated in FIG. 4J (the third exemplary device state of the exemplary device 9). The active medium **1608** when in the gain state at λ (State J in FIG. 4J) will be driven back to the transparency state at λ (State H in FIG. 4H) when the applied voltage V of the variable voltage source **1606** decreases to

become approximately equivalent to the transparency voltage at $V = V\big|_{c=c,(\lambda)}$.

The state of the active medium **1608** is again analogous to State H, as illustrated in FIG. 4H (the second exemplary device state of the exemplary device 9). This state (State H of FIG. 4H) is characterized by a relatively low electron excitation compared with State J of FIG. 4J (the third exemplary device state of the exemplary device 8).

When the voltage V is further reduced from $V\big|_{c=c,(\lambda)}$ to zero and then to a reverse bias (V<0), any excited electrons will be de-excited and the medium will be driven to and will maintain a loss state. The state of the active medium **1608** is again analogous to State K, as illustrated in FIG. 4K (the first exemplary device state of the exemplary device 9).

vii) Exemplary Device 9 as a Switching or Modulation Element

For a given light input at λ **1618**, in the case of device **1600** of FIG. 14 the net effect of varying the voltage applied to the active medium **1608** is that the increasing the applied voltage V to $V\big|_{c=c,(\lambda)}$ generates light at λ **1620** exiting port B2 **1614** on Waveguide B **1604**, while decreasing the applied voltage V below approximately zero volts results in light at λ **1616** exiting port A2 **1612** on Waveguide A **1602**. In this way, the electro-optic phosistor **1600** can be used as a voltage-controlled switching element between the first and the second exemplary states described above, and can act as an optical switch that switches optical energy between output A2 **1612** and output B2 **1614**.

It should be understood that this description covers several but not all aspects of device performance. For example, the light at λ ($\lambda \geq \lambda_{gap}$) can be on or off, and if the light at λ is on, the intensity I_λ of the light at λ can be greater than, equal to, or less than the saturation intensity of the active medium **1608**. In addition, the PN or PIN junction that preferably includes the active medium **1608** can be forward (approximately V>0) or reverse (V approximately <0) biased by the applied voltage V of the variable voltage source **1606**. The

applied voltage V has an associated injection current C. As shown above,

when V exceeds zero volts (approximately), the value of V relative to the

transparency voltage at $C=C_t(\lambda)$ has implications for the operation of the

device **1600** and the state of the active medium **1608**. The active medium

1608 can exhibit loss, transparency, or gain at the wavelength of operation λ

depending on the light intensity at λ and the applied voltage V and/or injection

current C. It should be understood however that more or fewer states of the

active medium can be applied to and described instructively with respect to

device **1600** in this or in other useful embodiments and/or applications.

In another useful embodiment of the device **1600**, the active medium

1608 does not contain a PN or PIN junction, and the quantum contained stark

effect or the Franz-Keldysh effect is used to change the medium from

transparency to absorption under an applied voltage across the active

medium **1608**. The device otherwise functions in a way identical to the

exemplary device 9. In this case, the first exemplary state will correspond to

state F in FIG. 4F and the second exemplary state will correspond to state E

in FIG. 4E.

viii). Exemplary Device 9 as a Phase Shifter

In another useful embodiment of the device, the waveguide interaction

length is approximately $2\ell_c$ ($\ell \cong \ell_c$) or an even number multiple of ℓ_c

($\ell \cong 2m\ell_c$, where m is a positive integer). In this case, when the active

medium **1608** is in a state of transparency as in state H of FIG. 4H, the signal

light input **1618** will first propagate along Waveguide A **1602** but will have

most of the energy transferred from Waveguide A **1602** to Waveguide B **1604**

after propagating for a length of ℓ_c. This energy will be transferred from

Waveguide B **1604** back to Waveguide A **1602** after the light further

propagates for another length of ℓ_c, resulting in signal output at λ from port

A2 **1612** if $\ell = 2\ell_c$. When the active medium is in a state of loss as in state K

of FIG. 4K, **most of** the signal light input **1618** will not transfer from

Waveguide A **1602** to Waveguide B **1604** as it propagates but will propagate

only along Waveguide A **1602** and exit port A2 **1612**. However, the signal light will experience a different phase shift due to the different pathway it takes to get to port A2 **1612**. Specifically, it will attain a change of phase shift by π radians (or 180°).

Hence, the net action is that the signal light will exit the same port A2 **1618** when the active medium changes from the first state to the second state but with a change in the optical phase by π radians (or 180°). In this case, the device functions as a voltage-controlled optical phase shifter.

viiii). Exemplary Device 9 as a Wavelength Multiplexer/De-Multiplexer or Wavelength Selective Switch

In another useful embodiment of the device, the waveguides A and B have unequal widths W_A and W_B. As is well known to those skilled in the art, waveguide couplers with unequal waveguide widths will have strong wavelength sensitivity. In particular, when the active medium is in the transparency state, only certain wavelength of light will couple maximally from waveguide A to waveguide B, thus allowing the device to act not only as a switch but as a wavelength selective switch. Except for the difference in the waveguide widths providing wavelength sensitivity, this embodiment of the device is otherwise functionally and operationally identical to the device **1600** and descriptions and comments relating to the device **1600** are generally applicable to this device.

x).   MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator I/Resonator II configuration for device 9 would be topologically similar to the MMI/ Resonator I/Resonator II configuration of Device 2. As in device 2, it should be understood that the MMI/Resonator I/Resonator II Configuration Devices are otherwise functionally and operationally identical to the device **1600** and descriptions and comments relating to the device **1600** are generally applicable to the MMI/Resonator I/Resonator II Configuration

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Devices. The use of resonators can help to reduce the required operating voltage of the device as well as the device size.

xi).   PBG Implementation of the Coupler/MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 9 would be topologically similar to the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 2. As in device 2, it should be understood that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 9 are otherwise functionally and operationally identical to the device **1600** and descriptions and comments relating to the device **1600** are generally applicable to the PBG implementations.

As with the previous embodiments, it should be understood that the dimensions and materials for the devices are presented for purposes of illustrating a useful embodiment of the device **1600** and its MMI/PBG/Resonator versions, and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1600** its MMI/PBG/Resonator versions. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety of materials can be used, for examples, the waveguides do not have to be semiconductors and may be optical fibers or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved), the active medium does not have to be a semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite gain/loss/transparency properties are achieved), and the resonators do not have to be semiconductors but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the shape of the Waveguides, MMI Structures, Photonic Bandgap Structures, or Resonators does not generally have to be linear, circular, parallel, or regular

in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

It should be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the refractive index of the active medium could occur when the active medium changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the working of these devices include those cases whereby both the gain/transparency/loss property as well as the refractive-index property of the active medium are used in bringing about the device operation.

C.   EXEMPLARY DEVICE 10 (A THREE GATE ELECTRO-OPTIC DEVICE)

FIG. 15 illustrates a tenth exemplary device and a second general embodiment **1700** of an electro-optic phosistor device employing directionally coupled waveguides. For purposes of illustration and not limitation, the device is described according to one useful function as a switching element for slow or ultrafast optical pulses of sufficient energy and wavelength. The device **1700** is not limited to use as a switching element for a single light input and can be utilized as, for example, as an M x N switch, a variable coupling device (including its use in an optical loop mirror and a pulse storage ring), an electro-optic phase shifter, a resonator frequency tuning element, a light intensity modulator, a light intensity regulator, and a variable optical attenuator. It should be understood that these exemplary applications of device **1700** are intended to illustrate the wide range of uses for device **1700**, and are not intended to limit the applications or other exemplary embodiments

of device **1700** to these examples. The device can be referred to as an "Electro-Optic Mid-Arm-Gain-Loss Gate Phosistor" (EO MGL Phosistor **1700**).

It should be understood that the phosistor device **1700** as presented in FIG. 15 can also be employed as an all-optical device by utilizing input light to modify the state of the active medium (with respect to an operating wavelength of other input light) to affect the interference and light transfer properties of the device **1700** in the way described with exemplary devices 1 through 7, rather than through the application of a voltage or the injection of current.

EO MGL Phosistor **1700** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **1702** and a second pathway of light consisting of the spatial region occupied by Waveguide B **1704**, and a third waveguide G **1722**. The Waveguide G **1722** preferably includes an active medium **1708**. A Voltage Source **1706** having a variable voltage V is applied across the active medium **1708**. Waveguide G **1722** can be implemented as waveguide **450** illustrated in FIG. 5D with active medium **420**. Waveguide A **1702** and waveguide B **1704** can be implemented as Waveguide **400** illustrated in FIG. 5A in a useful embodiment. The Waveguide A **1702** preferably includes an input port A1 **1710** and an output port A2 **1712**. The Waveguide B **1704** preferably includes an input port **1724** and an output port B2 **1714**. The Waveguide G **1722** preferably includes an input port G1 **1726** and an output port G2 **1728**, as well as the active medium **1708**. FIG. 15 illustrates that Waveguide A **1702** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_{gAG} from Waveguide G **1722**, which has width W_G. Waveguide G **1722** is in turn located at an approximately parallel distance (coupling gap or distance) W_{gGB} from Waveguide B **1704**, which has width W_B.

The input port A1 **1710** on the Waveguide A **1702** is configured to receive light having wavelength λ (at λ) (SIGNAL IN λ) **1718**. In a useful embodiment, this light at λ **1718** is continuous wave (CW) light. Depending on the state of the electro-optic phosistor **1700**, light can be output from the output port B2 **1714** as light having wavelength λ (at λ) (ON-SIGNAL OUT λ)

1720. In a useful embodiment, this light at λ **1720** is pulsed light. Light is also capable of being output from the output port A2 **1712** as light having wavelength λ (at λ) (OFF-SIGNAL OUT λ) **1716**. In a useful embodiment, this light at λ **1716** is pulsed light. Under certain operating conditions described

5   below when the active medium on the waveguide reaches transparency and Waveguides A, B, and G are optically transparent, most of the CW light at λ **1718** propagating along the Waveguide A **1702** will be transferred to Waveguide B **1704** after a coupling length ℓ'_C. It should be understood that the light signals into and out of MGL Phosistor **1700** and other useful

10   embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

The coupling length $\ell'_C|_{X-Z-Y}$ is defined as the length at which a wave in a first waveguide (X) maximally couples into a second waveguide (Y) that is

15   coupled to the first waveguide (X). There may be one or more intermediate waveguides between waveguides X and Y, which can be represented by one waveguide (Z). As is known to those skilled in the art, the coupling length is a function of the gap distance between each pair of waveguides and the width of each waveguide. The gap distances can be chosen to achieve maximal

20   coupling between waveguide X and waveguide Y through intermediate coupling between waveguide X to waveguide Z and waveguide Z to waveguide Y, where Z can represent one or more waveguides.

In this device **1700**, the interaction length ℓ', defined as the length of interaction between waves in Waveguides A **1702**, G **1722**, and B **1704**

25   extends to approximately the full coupling length ℓ'_C so that $\ell' = \ell'_C$ in one useful embodiment of the device but can be different from ℓ'_C in other useful embodiments of the device. In the case of FIG. 15, the interaction length is defined geometrically by the length for which waveguides A, G, and B run closely parallel to each other.

30   As shown in FIG. 15, the length L of the active medium **1708** is about equal to the interaction length ℓ' ($L = \ell'$). The length L of the active medium

1708 may be somewhat longer or shorter than ℓ'. Varying the length L of the active medium **1708** relative to the interaction length ℓ' will vary the input to output signal conversion efficiency but will otherwise not affect the general operating principle of the device.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **1700** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **1700**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell' = \ell'_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ'_c and still achieve similar device functions.

Also, it should be understood that the shape of the waveguides does not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. The active medium can be centered at an alternative location along waveguide B other than that illustrated in FIG. 15, and there can be more than one disconnected active medium areas along waveguide B. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also coupled waveguides do not have to be exactly parallel or have the same widths and dimensions as long as the desired effect of wave-coupling is achieved.

In an exemplary embodiment of device **1700** for operation at 800nm wavelength range, the wavelength λ can be at 820nm and the Waveguides A **1702** and B **1704** can be implemented as the Waveguide **400** illustrated in FIG. 5A and Waveguide G **1722** can be implemented as the Waveguide **450** with an active medium **420** illustrated in FIG. 5D, in an $Al_xGa_{1-x}As$ embodiment for the waveguide core having alloy composition x = 0.3 giving a

bandgap energy of around 690nm. Thus the core material in waveguides A, B, and G is transparent at the wavelength λ of 820nm. When the active medium in waveguide G is fully de-excited, the active medium absorbs light at 820nm wavelength. The active medium is an essentially three-level medium for which the electrons supplied from current injection are free to relax from an upper-energy level to the upper-energy level corresponding to the 820nm absorption.

In an exemplary embodiment of device **1700** for operation at 1500nm wavelength range, the wavelength λ can be at 1500nm and the Waveguides A **1702** and B **1704** can be implemented as the Waveguide 400 illustrated in FIG. 5A and Waveguide G **1722** can be implemented as the Waveguide **450**. Both have an active medium **420** illustrated in FIG. 5D, in an $\underline{In_{1-x}Ga_xAs_{1-y}P_y}$ embodiment for the waveguide core having alloy compositions x=0.16 and y=0.67 giving a bandgap energy of around 1100 nm. Thus the core material in waveguides A, B, and G is transparent at the wavelength λ of 1500nm. When the active medium in waveguide G is fully de-excited, the active medium absorbs light at 1500nm wavelength. The active medium is an essentially three-level medium for which the electrons supplied from current injection are free to relax from an upper-energy level to the upper-energy level corresponding to the 1500nm absorption.

In an exemplary embodiment for application to the 1500nm (or 1.5 μm) wavelength range, the cross-sectional dimensions of the waveguide **400** or **450** are 0.4 μm wide by 0.25 μm thick. In an exemplary embodiment, the Waveguide A **1702** has width W_A equal to 0.4 μm and is located at an approximately parallel distance W_{gAG} from Waveguide G **1722** of 0.3 μm, while the Waveguide G **1722** has width W_G equal to 0.4 μm. In this embodiment, the Waveguide G **1722** is in turn located at an approximately parallel distance W_{gGB} from Waveguide B **1704** of 0.3 μm, while the Waveguide B **1704** has width W_B equal to 0.4 μm. The material refractive indices of the Waveguides A, the Waveguide G, and the Waveguide B are denoted as n_A, n_B, and n_C, respectively, and are taken to be $n_A=n_B=n_G=3.4$.

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These refractive indices give an effective planar-waveguide propagating refractive index of about 2 in a planar waveguide structure with a thickness of 0.25 μm. The material refractive index outside the waveguides is taken to be 1.5. In this exemplary embodiment for which the wavelengths of light are at around 1500nm range, ℓ'_c is about 15 μm.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **1700** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **1700**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i)   General Operating Principle for the Device

The main action of the injection current or applied voltage to the active medium preferably is to bring the medium from a state of loss or transparency to a state of gain. The loss, transparency, or gain state of the medium then affects the transfer of light from various inputs to various outputs. The general operation of the device can be illustrated via computer simulation of such light transfer as a function of the medium's loss/gain coefficient (gain and loss coefficients are related as gain coefficient can be described as negative loss coefficient).

An exemplary operation of the device can be illustrated via the results of computer simulation as shown in FIGs. 15A, 15B, and 15C. FIGs. 15A and 15B show the spatial distribution of the electric field strength for the light input at λ **1718** after propagating into waveguides A and B. The upper parts of FIGs. 15A and 15B are 2-D plots for which the brightness shows the relative field strength, and the lower parts of FIGs. 15A and 15B are 3-D plots for which the heights show the relative field strength. FIG. 15C shows the relative power at the output ports of waveguide A (port A2, **1712**) and waveguide B (port B2, **1714**) as a function of –gL (the product of the loss coefficient –g and the medium length L). In FIG. 15C, the output at A2 is shown as a dotted line,

the output at B2 is shown as a dashed line, and the solid line is the sum of the outputs at A2 and B2 (i.e. the dashed line plus the dotted line). FIG. 15A shows the situation when the gain medium is in the state of transparency (at a loss coefficient of 0 per μm or −gL=0). From FIG. 15A, it is evident that most

5   of the energy of λ **1718** exits from Waveguide B **1704** at the port B2 **1714**. FIG. 15B shows the situation when the medium is de-excited to the state of loss at λ by the pulsed light at λ **1722** (at a gain coefficient of about 3.3 per μm or −gL=50). From FIG. 15B, it is evident that most of the energy of λ exits from Waveguide A. FIG. 15A and FIG. 15B show the two representative

10   interference flux patterns of light for the device, which is dependent on the state of the active medium. In particular, one can switch between these two representative interference flux patterns of light by changing the state of the active medium through the action of an applied voltage or injection current. Note that besides these two states, there are other states, for example the

15   intermediate state at −gL=6 shown in FIG. 15C, for which there is substantial total energy absorbed by the loss medium so that both output ports at waveguide A and waveguide B have low output power.

In FIG. 15D, we show the case of a longer device for which the gap W_g is 1.2 μm instead of 0.4 μm, and the coupling length ℓ'_c is 120 μm. Again the

20   interaction length ℓ' is set equal to ℓ'_c and the medium length L is equal to ℓ'_c. FIG. 15D shows the relative powers at the output ports of waveguide A (port A2) and waveguide B (port B2) as a function of gL (the product between the gain coefficient g and the medium length L). Comparing FIG. 15C and FIG. 15D, we see that the switching is more complete for the longer device

25   case of FIG. 15D. While switching still occurs at a gL of about -50, a longer L means a short g (for gL=-50, L=120 μm, we have g=0.4/μm), which means the switching voltage can be lower.

ii) Exemplary Device States

30   Various operating modes of a general active region or medium (such as active medium **420** operating as a PN or PIN junction) with an applied

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voltage V (or injection current C) were defined and described above and illustrated in FIG. 4G-K. Since the electro-optic phosistors such as device **1700** and related exemplary embodiments thereto preferably include one or more active regions, the devices and embodiments thereto can be

5   characterized according to the states illustrated in FIG. 4G-K.

In a preferred and useful embodiment, the electro-optic phosistor **1700** operates as a switching element. The wavelength of the light at λ input to the device **1700** is preferably around the bandgap energy (associated with λ_{gap}).

It should be understood that the light signals into and out of MGL

10   Phosistor **1700** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

It should be understood that the action of the exemplary Phosistor

15   **1700** is defined by the paths taken by the light beams in the device **1700**. The paths taken by the light beams in the device **1700** are preferably dependent on the state of the active medium in the interaction region of the Phosistor **1700** (e.g. state of loss, transparency, or gain).

The combination of the state of the active medium and the state of light

20   beam propagation in the device define the state of the device. The various operations of the device **1700** can be more precisely described in terms of such device states. It should be understood however that more or fewer device states can be applied to and described instructively with respect to device **1700** in this or in other useful embodiments and/or applications.

25   In particular, the operation of the device can be described as making transitions from one class of states to another class of states under the influence of some external inputs such as the power of the input beam, the locations where the input beam is received, and applied electrical energy, preferably including applied voltages or currents.

iii).   A First Exemplary Device State

For this first exemplary device state of the electro-optic phosistor **1700**, the light beam at λ **1718** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1718** can be greater than, equal to, or less than the saturation intensity I_{sat} of the active medium **1708**. The voltage V of the variable voltage source **1706** that is applied across the PN or PIN junction including the active medium **1708**, is approximately less than or equal to zero volts. At this value, the PN or PIN junction including the active medium **1708** is reverse-biased by the applied voltage V.

Light at λ **1718** enters at the port A1 **1710** on the Waveguide A **1702**. The light at λ **1718** propagates along the Waveguide A **1702** and loses energy in the active medium **1708** so that most of the light at λ **1718** does not transfer via Waveguide G **1722** to Waveguide B **1704** and thus does not exit from the output on B2 **1714**. Rather, most of the light at λ **1718** propagates through Waveguide A **1702** and exits from Waveguide A **1702** at the port A2 **1712** as light at λ **1716**. The reverse bias from the applied voltage V drives the active medium **1708** to a state of loss at λ and maintains this state while the applied voltage V is approximately at or below zero volts. This state of the active medium **1708** is analogous to Case K, as illustrated in FIG. 4K.

iv).   A Second Exemplary Device State

For this second exemplary device state of the electro-optic phosistor **1700**, the light beam at λ **1718** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1718** can be greater than, equal to, or less than the saturation intensity I_{sat} of the active medium **1708**. The voltage V of the variable voltage source **1706** that is applied across the PN (or PIN) junction including the active medium **1708**, is approximately equal to the value

of the voltage that is associated with a critical value of the injection current, $C_t(\lambda)$, called the transparency current. At this value, the PN or PIN junction including the active medium **1708** is forward-biased by the applied voltage V. This transparency current, $C_t(\lambda)$ is the approximate value of the current when the active medium **1608** is driven to a state of transparency at wavelength λ by the current. The corresponding voltage $V\big|_{c=c_t(\lambda)}$ that gives rise to this transparency current $C_t(\lambda)$, is called the transparency voltage. This state of the active medium is analogous to State H as illustrated in FIG. 4H.

Light at λ **1718** enters at the port A1 **1710** on the Waveguide A **1702**. The light at λ **1718** propagates along the Waveguide A **1702** and is subsequently transferred from Waveguide A **1702** to Waveguide B **1704** via waveguide G **1722** after a coupling length ℓ'_c. The light at λ **1718** then exits from Waveguide B **1704** at the port B2 **1714** as light at λ **1720**. While the applied voltage V is approximately at the transparency voltage $V\big|_{c=c_t(\lambda)}$, the active medium **1708** is driven to and maintained in a state of transparency at λ. Not enough electrons are supplied by the applied voltage/injection current to drive the active medium to a gain state at λ. This state of the active medium **1708** is analogous to Case H, as illustrated in FIG. 4H.

v).   A Third Exemplary Device State

For this third exemplary device state of the electro-optic phosistor **1700**, the light beam at λ **1718** is turned "on." The wavelength λ is at the wavelength of absorption and gain of the active medium, which is slightly shorter than the bandgap wavelength λ_g of the active medium ($\lambda < \lambda_g$). The intensity I_λ of the light beam at λ **1718** can be greater than, equal to, or less than the saturation intensity I_{sat} of the active medium **1708**. The voltage V of the variable voltage source **1706** that is applied across the PN (or PIN) junction including the active medium **1708**, is greater than the value of the

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voltage that is associated with a critical value of the injection current, C_t (i.e.,

$V > V\big|_{C=C_t(\lambda)}$).

As the applied voltage V of the variable voltage source **1706** increases

beyond the voltage at $V = V\big|_{C=C_t(\lambda)}$, the applied voltage V will excite the active

5   medium **1708**, providing gain at the operating wavelength λ to the active

medium **1708** located in Waveguide G **1722**. This state of the active medium

1708 is analogous to Case J, as illustrated in FIG. 4J.

This state (state J of FIG. 4J) is characterized by a relatively fast

electron excitation due to the increased injection current C and applied

10   voltage V compared with the first exemplary state of the exemplary device

(state H of FIG. 4H).

The light at λ **1718** from input port A1 **1710** transfers from Waveguide

A **1702** to Waveguide B **1704** via Waveguide G **1722** and gains energy in the

active medium **1708** located on Waveguide G **1722,** and some extra energy

15   propagates towards and exits port A2 **1712**.   .

vi).   Transitions for the Active Medium States and Device States

Transition from one active medium state to another is brought about by

changing the applied voltage. The change in the active medium state then

20   brings about a corresponding change in the device state, resulting in a

change in the behavior of the light beams propagating through the device.

As an example of such transitions, suppose we start with a forward-

biased voltage at above the transparency voltage $V > V\big|_{C=C_t(\lambda)}$. In this case,

the active medium **1708** is in the state of gain analogous to State J, as

25   illustrated in FIG. 4J (the third exemplary device state of the exemplary device

9). The active medium **1708** when in the gain state at λ (State J in FIG. 4J)

will be driven back to the transparency state at λ (State H in FIG. 4H) when

the applied voltage V of the variable voltage source **1706** decreases to

become approximately equivalent to the transparency voltage at $V = V\big|_{C=C_t(\lambda)}$.

30   The state of the active medium **1708** is again analogous to State H, as

illustrated in FIG. 4H (the second exemplary device state of the exemplary device 9). This state (State H of FIG. 4H) is characterized by a relatively low electron excitation compared with State J of FIG. 4J (the third exemplary device state of the exemplary device 8).

5   When the voltage V is further reduced from $V\big|_{c=c_i(\lambda)}$ to zero and then to a reverse bias (V<0), any excited electrons will be de-excited and the medium will be driven to and will maintain a loss state. The state of the active medium **1708** is again analogous to State K, as illustrated in FIG. 4K (the first exemplary device state of the exemplary device 9).

10   ### vii).   Exemplary Device 10 as a Switching Element

In the case of FIG. 15 the net effect of varying the voltage applied to the active medium **1708** is that increasing the applied voltage V to

$V\big|_{c=c_i(\lambda)}$ generates light at λ **1720** exiting port B2 **1714** on Waveguide B **1704**, while decreasing the applied voltage V below approximately zero volts results

15   in light at λ **1716** exiting port A2 **1712** on Waveguide A **1702**. In this way, the electro-optic phosistor **1700** can be used as a voltage-controlled switching element between the first and the second exemplary states described above.

The device has a symmetric property in that port B1 **1724** can play the role of a signal input port as in port A1 **1710**. In this case, port A2 **1712** (or B2

20   **1714**) will play the role of output port B2 **1714** (or A2 **1712**). Likewise, port A2 **1712** can play the role of the signal input port A1 **1710** and port B1 **1724** (or A1 **1710**) will then play the role of the signal output port B2 **1714** (or A2 **1712**). Lastly, port B2 **1714** can play the role of the signal input port A1 **1710** and port A1 **1710** (or B1 **1724**) will then play the role of the signal output port B2 **1714**

25   (or A2 **1712**).

The above symmetric property of the device allows it to be used in particular as a 2x2 optical cross-bar switch. In this case, there will be a signal input at λ1 (signal 1) into port A1 **1710** and another signal input at λ2 (signal 2—not shown in FIG. 15) into port B1 **1724**. The wavelengths λ1 and

λ2 may be the same or may be different for the two separate signal light beams (signal 1 and signal 2).

Depending on the state of the medium, it is possible to channel signal 1 to output port A2 **1712** and signal 2 to output port B2 **1714** or signal 1 to output port B2 **1714** and signal 2 to output port A2 **1712**. Specifically in the bar state output, the active medium **1708** is driven to a loss state as in state K of FIG. 4K. In this case, signal input at λ1 in port A1 **1710** will propagate along Waveguide A **1702** and exit port A2 **1712** and signal input at λ2 in port B1 **1724** will propagate along Waveguide B **1704** and exit port B2 **1714**.

In the cross-state output, the active medium **1708** is driven to a transparency state as in state H of FIG. 4H. In this case, **most of signal** output at λ1 in port A1 **1710** will couple from Waveguide A **1702** to Waveguide B **1704** and exit port B2 and most of signal input at λ2 in port B1 **1724** will couple from Waveguide B **1704** to Waveguide A **1702** and exit port A2.

Hence, the net effect is that changing from the first state to the second state will bring the device from a bar-state output to a cross-state output. Operated in this fashion, the device is known to those skilled in the art as a 2x2 optical cross-bar switch. 2x2 cross-bar switches can be mutually connected in such a way as to implement a MxN cross-bar switching in which signals input into M designated input ports can be channeled in any order to N output ports.

It should be understood that this description covers several but not all aspects of device performance. For example, the light at λ ($\lambda \geq \lambda_{gap}$) can be on or off, and if the light at λ is on, the intensity I_λ of the light at λ can be greater than, equal to, or less than the saturation intensity of the active medium **1708**. In addition, the PN (or PIN) junction that preferably includes the active medium **1708** can be forward (approximately V>0) or reverse (V approximately <0) biased by the applied voltage V of the variable voltage source **1706**. The applied voltage V has an associated injection current C. As shown above, when V exceeds zero volts (approximately), the value of V

relative to the voltage at $C=C_t(\lambda)$ has implications for the operation of the device **1700** and the state of the active medium **1708**. The active medium **1708** can exhibit loss, transparency, or gain at the wavelength of operation λ depending on the light intensity at λ and the applied voltage V and/or injection current C. It should be understood however that more or fewer states of the active medium can be applied to and described instructively with respect to device **1700** in this or in other useful embodiments and/or applications.

In another useful embodiment of the device **1700**, the active medium does not contain a PN or PIN junction, and the quantum contained stark effect or the Franz-Keldysn effect is used to change the medium **1708** from transparency to absorption under an applied voltage across the active medium **1708**. The embodiment otherwise functions in an identical way as the exemplary device 10 **1700** as described above. In this case, the first exemplary state will correspond to state F in FIG. 4F and the second exemplary state will correspond to state E in FIG. 4E.

viii). Exemplary Device 10 as a Phase Shifter

As in the case of Device 10, by choosing coupling length ℓ'_c so that $\ell''= 2\ell'_c$, light input into waveguide A will be coupled back to waveguide A, the net result of which is an additional optical phase shift, whose value will depend on how many intermediate waveguides are coupled to. Typically the phase shift will be in multiple number of π radians (or 180°). When the active medium is in the loss state, light will remain in waveguide A (i.e. there will be no coupling to other waveguides) and there will be no additional optical phase shift. In this way, Device 10 can function as an electro-optically controlled phase shifter.

viiii). Exemplary Device 10 as a Wavelength Multiplexer/De-Multiplexer or Wavelength Selective Switch

In another useful embodiment of the device, the waveguides A, G, and B have unequal widths W_A, W_G, and W_B. As is well known to those skilled in

the art, waveguide couplers with unequal waveguide widths will have strong wavelength sensitivity. In particular, when the active medium is in the transparency state, only certain wavelengths of light will couple maximally from waveguide A to waveguide B, thus allowing the device to act not only as a switch but as a wavelength selective switch. As an exemplary embodiment, the width W_A and W_B can be equal to 0.4 μm and W_G can be equal to 0.6 μm. Except for the difference in the waveguide widths providing wavelength sensitivity, this embodiment of the device is otherwise functionally and operationally identical to the device **1700** and descriptions and comments relating to the device **1700** are generally applicable to this device.

x). MMI/Resonator Configuration Device

It should be evident to those skilled in the art that the MMI/Resonator I/Resonator II configuration for device 10 would be topologically similar to three-gate implementation of MMI/ Resonator I/Resonator II configuration of Device 2. As in device 2, it should be understood that the MMI/Resonator I/Resonator II Configuration Devices are otherwise functionally and operationally identical to the device **1700** and descriptions and comments relating to the device **1700** are generally applicable to the MMI/Resonator I/Resonator II Configuration Devices.

xi). PBG Implementation of the Coupler/ MMI/ Resonator Configuration Device

It should be evident to those skilled in the art that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 9 would be topologically similar to the PBG implementations for the three-gate version of the Coupler/ MMI/ Resonator I/ Resonator II configuration of device 2. As in device 2, it should be understood that the PBG implementations for the Coupler/MMI/Resonator I/Resonator II configuration of device 9 are otherwise functionally and operationally identical to the device **1700** and descriptions and comments relating to the device **1700** are generally applicable to the PBG implementations.

As with previous embodiments, it should be understood that the dimensions and materials for the devices are presented for purposes of illustrating a useful embodiment of the device **1700** and its MMI/PBG/Resonator versions, and are not intended to limit other exemplary

5   embodiments of any exemplary device, or the device **1700** and its MMI/PBG/Resonator versions. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. A variety of materials can be used, for examples, the waveguides do not have to be semiconductor

10   and may be optical fibers or polymer waveguides (as long as the requisite waveguiding or wave-coupling effect is achieved), the active medium does not have to be semiconductor or quantum well but can be erbium ions doped in glass or active polymers (as long as the requisite gain/loss/transparency properties are achived), and the resonators do not have to be semiconductor

15   but can be glass or polymers (as long as the requisite resonance effect is achieved). Also, it should be understood that the shape of the Waveguides, MMI Structures, Photonic Bandgap Structures, or Resonators do not generally have to be linear, circular, parallel, or regular in form. Arbitrarily curved shapes and structural dimensions may be utilized as long as they achieve the

20   same functions such as waveguiding, wave-coupling, optical resonant effect, and photonic bandgap effect.

It should be understood that while the active medium of these devices works primarily in the gain/transparency/loss modes, concurrent change in the refractive index of the active medium could occur when the active medium

25   changes state. The change in the active medium's refractive index can in some cases be used to further improve the device performance. Thus, the working of these devices include those cases whereby both the gain/transparency/loss property as well as the refractive-index property of the active medium are used in bringing about the device operation.

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· D.   EXEMPLARY DEVICE 11 (A WAVELENGTH MULTIPLEXING/ FILTERING DEVICE)

FIG. 16 illustrates a general embodiment **2100** of a phosistor device employing a multimode interference filter. The device is capable of performing as an optical filter and is also capable of shifting the resonance frequency of the filter via an applied voltage or injection current. The device can be referred to as a "wavelength-multiplexing phosistor" (WM Phosistor **2100**).

It should be understood that the phosistor device **2100** as presented in FIG. 16 can also be employed as an all-optical device by utilizing input light to modify the state of the active medium (with respect to an operating wavelength of other input light) to affect the interference and light transfer properties of the device **2100** in the way described with exemplary devices 1 through 7, rather than through the application of a voltage or the injection of current.

WM Phosistor **2100** preferably includes an input Waveguide A **2102**, an output Waveguide B **2104**, and a multimode interference (MMI) Waveguide MMI **2116** and two Bypass Waveguides C **2105** and D **2106**. The multimode interference MMI Waveguide **2116** preferably includes an active medium **2108**. As described above, Waveguide A **2102** can be implemented as waveguide **450** with active medium **420** in a useful embodiment. The Waveguide A **2102** preferably includes an input port A1 **2120** and is preferably connected to the MMI Waveguide **2116** as illustrated in FIG. 16. Light at λ **2118** entering port A1 **2120** will propagate into the MMI Waveguide **2216** region, which in an exemplary embodiment has a waveguide width approximately three times larger than the width of Waveguide A **2102**.

FIG. 17A illustrates a possible interference flux pattern of light formed by the light at λ **2118** entering the MMI Waveguide **2216** region. As shown in FIG. 17A, along the center of the MMI Waveguide **2216** region there is a point or location at which the field energy is low, as indicated at point Z **2117**.

There is also a point or location at which the field energy is maximal. In an exemplary embodiment, the length ℓ of the MMI Waveguide **2116** is designed so that at a joining interface **2126** between the MMI Waveguide **2116** and the output Waveguide B **2104**, the field energy is at its maximum. In this case, most of the signal light energy (from the light at λ **2118**) will couple from the MMI Waveguide **2116** to the output Waveguide B **2104**, resulting in a substantial transfer of signal light energy from the input port A1 **2120** to the output port B2 **2122**.

FIG. 17B illustrates another possible interference flux pattern of light, similarly formed by the light at λ **2118** entering the MMI Waveguide **2216** region. Increasing the length of the input wavelength λ of the light **2118** will in general shift the interference flux pattern of light to the right so that at some wavelength λ, the zero energy area of the pattern ZZ **2124** is at the joining interface **2126** between the MMI Waveguide **2116** and the output Waveguide B **2104**. In this case, essentially most of the signal light energy will be coupled into the Bypass Waveguides C **2103** and D **2106** and out of output ports C2 **2128** and D2 **2130**, respectively, resulting in little or no energy transferring from the input port A1 **2120** to the output port B2 **2122**.

Hence, the energy transfer from the input port A1 **2120** to the output port B2 **2122** depends on the input wavelength λ and the device **2100** can be utilized as an optical wavelength filter. As is known to those skilled in the art, the wavelengths that yield a maximal transfer of signal energy are called resonant wavelengths.

The above description assumes that the active medium **2108** of device **2100** is in the transparency state at λ as in state H of FIG. 4H. Driving the active medium to a state of loss at λ as in state K of FIG. 4K or F of FIG. 4F, however, for example via an externally applied voltage (not illustrated in FIG. 16), will shift the resonance wavelength because of the change in the interference flux pattern of light in the MMI Waveguide **2116**.

The distance between adjacent resonance wavelengths (called the filtering resolution) is inversely proportional to the length ℓ of the MMI

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Waveguide **2116**. By choosing ℓ to be large, in the millimeter range, it is possible to achieve a very small filtering resolution on the order of a few nanometers. In an exemplary embodiment of device **2100** shown in FIG. 16, ℓ is four (4) microns in length. In a useful embodiment, the widths W_A, W_B, W_C, and W_D of the Waveguides A **2102**, B **2104**, C **2105**, and D **2106**, respectively are each 0.235 microns, while the width W_{MMI} of the MMI Waveguide **2116** is 0.675 microns and the width W_{MED} of the active medium **2108** is 0.235 microns. It should be understood, however, that ℓ is not limited to micron or millimeter length in other embodiments of the device **2100**, and in general that the dimensions relating to the exemplary embodiments of device **2100** are not limited to the dimensions illustrated in FIG. 14.

It should be understood that these dimensions and exemplary lengths are presented for purposes of illustrating a useful embodiment of the device **2100** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **2100**. A variety of dimensions and sizes can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

It should be understood that FIG. 16 is presented not only to describe the operation of an application such as an optical wavelength filter, but also to illustrate the applicability of multimode interference (MMI) technology and devices to the all-optical and electro-optical devices described herein. As will be evident to those skilled in the art, each of the exemplary embodiments of the directional coupled waveguides can be implemented as MMI devices in useful embodiments.

E.   EXEMPLARY DEVICE 12 (A THREE GATE MECHANICAL-OPTICAL DEVICE)

FIG. 18 illustrates a twelfth exemplary device and a first general embodiment **2300** of a mechanical-optical phosistor device employing directionally coupled waveguides. For purposes of illustration and not limitation, the device is described according to one useful function as a switching element for slow or ultrafast optical pulses of sufficient energy and wavelength. The device **2300** is not limited to use as a switching element and can instead be used to implement other mechanical-optical device functions to perform in various applications. It can be utilized, for example, as a MxN optical cross-bar switch, a variable coupling device (including an optical loop mirror and a pulse storage ring), a mechanical-optical phase shifter, a resonator frequency tuning element, a light intensity modulator, a light intensity regulator, a micro-electro-mechanical optical switch, a micro-acousto-mechanical optical switch, a micro-hydro-mechanical optical switch, and a variable optical attenuator. The device can be referred to as an "Mechanical-Optical Mid-Arm-Gate Phosistor" (MO-MG Phosistor **2300**).

MO-MG Phosistor **2300** preferably includes a first pathway of light consisting of the spatial region occupied by Waveguide A **2302**, a second pathway of light consisting of the spatial region occupied by Waveguide B **2304**, and a third Waveguide G **2322**. Waveguide G is suspended in air and is surrounded by bottom substrate area S **2370**, and areas A1 **2372**, A2 **2374**, and A3 **2376**, which are solid areas. Preferably, the Waveguide G **2322** includes no active medium but can be moved physically or mechanically by placing it on a cantilever pivoted at C **2303** defined by the beam between points C **2303** and C' **2301**. Such mechanical motion can be induced, for example, by applying force on part F **2308** along the cantilever, where part F **2308** is shown to have a width WF1 and a length WF2. As described below, switching action can be achieved either by moving the waveguide G **2322** vertically or by moving the waveguide G **2322** horizontally.

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As an exemplary embodiment of the device **2300** which allows vertical movement of waveguide G **2322,** the force can be induced, for example, via applying voltage to a pair of parallel metal plate in which one of the metal plates **2309** is attached to part F **2308** of the cantilever and another of the metal plates **2311** is situated on the substrate area below part F **2308.** Metal plate **2311** is preferably oriented parallel to metal plate **2309** and is spaced by a distance P1 from the bottom on part F **2308.** Metal plate **2311** can have an irregular shape other than that shown as long as it is around the area or adjacent to the area below part F **2308.** A voltage Source **2306** having a variable voltage V1 can be applied across the parallel pair of metal plates **2309** and **2311** to move waveguide G in a vertical direction pivoted around point C **2303.** These forces on part F **2308** can also be induced via other mechanical means, for example, acoustically, hydraulically, or via acceleration. We may refer to this exemplary embodiment as the vertical-motion embodiment of device **2300.**

Alternatively, as an exemplary embodiment of the device **2300** which allows horizontal movement of waveguide G **2322,** the waveguide G **2322** may be moved via a metal plate **2305** attached to part F **2308** but oriented vertically and a metal plate **2307** attached to area A1' **2373.** Metal plate **2307** is preferably oriented parallel to metal plate **2305** but spaced by a distance P2 away from metal plate **2305.** These vertical pairs of metal plate **2305** and **2307** can be used to move the cantilever horizontally (pivoted around point C **2303**) via applying a voltage V2 **2390** to the parallel metal plates **2305** and **2307.** These forces on part F **2308** can also be induced via other mechanical means, for example, acoustically, hydraulically, or via acceleration. We may refer to this exemplary embodiment as the horizontal-motion embodiment of device **2300.**

Similar device switching functions can be achieved by using either the vertical-motion embodiment or the horizontal-motion embodiment of the device **2300.**

In an exemplary embodiment, the Waveguides A **2302,** B **2304,** and G **2322** can each be implemented as the Waveguide **400** illustrated in FIG. 5A.

Waveguides A, B, and G are support from below in areas A1, A2, and A3 in which the lower cladding region is solid material such as silicon dioxide. The Waveguide A **2302** preferably includes an input port A1 **2310** and an output port A2 **2312**. The Waveguide B **2304** preferably includes an input port **2324** and an output port B2 **2314**. FIG. 18 illustrates that Waveguide A **2302** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_{gAG} from Waveguide G **2322**, which has width W_G. Waveguide G **2322** is in turn located at an approximately parallel distance (coupling gap or distance) W_{gGB} from Waveguide B **2304**, which has width W_B.

The input port A1 **2310** on the Waveguide A **2302** is configured to receive light having wavelength λ (at λ) (SIGNAL IN λ) **2318**. In a useful embodiment, this light at λ **2318** is continuous wave (CW) light. Depending on the state of the mechanical-optical phosistor **2300**, light can be output from the output port B2 **2314** as light having wavelength λ (at λ) (ON-SIGNAL OUT λ) **2320**. In a useful embodiment, this light at λ **2320** is pulsed light. Light is also capable of being output from the output port A2 **2312** as light having wavelength λ (at λ) (OFF-SIGNAL OUT λ) **2316**. In a useful embodiment, this light at λ **2316** is pulsed light. Under certain operating condition described below, most of the CW light at λ **2318** propagating along the Waveguide A **2302** will be transferred to Waveguide B **2304** through waveguide G **2322**. It should be understood that the light signals into and out of MO-MG Phosistor **2300** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

The coupling length $\ell'_c\big|_{x\text{-}z\text{-}y}$ is defined as the length at which a wave in a first waveguide (X) maximally couples into a second waveguide (Y) that is coupled to the first waveguide (X). There may be one or more intermediate waveguides between waveguides X and Y, which can be represented by one waveguide (Z). As is known to those skilled in the art, the coupling length is a function of the gap distance between each pair of waveguides and the width

of each waveguide. The gap distances can be chosen to achieve maximal coupling between waveguide X and waveguide Y through intermediate coupling between waveguide X to waveguide Z and waveguide Z to waveguide Y, where Z can represent one or more waveguides.

In this device **2300**, the interaction length ℓ', defined as the length of interaction between waves in Waveguides A **2302**, G **2322**, and B **2304** extends to approximately the full coupling length ℓ'_c so that $\ell' = \ell'_c$ in one useful embodiment of the device but can be different from ℓ'_c in other useful embodiments of the device. In the case of FIG. 18, the interaction length is defined geometrically by the length for which waveguides A, G, and B run closely parallel to each other.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **2300** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **2300**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed. For example, while the choice of $\ell' = \ell'_c$ is illustrated in this exemplary device, the interaction length may vary from the coupling length ℓ'_c and still achieve similar device functions. The structure forming waveguide G does not have to be of the regular shape shown. The overhanging of waveguide A and B is not necessary and waveguide A and B can be adjacent to the edge of the hole or indentation area.

Also, it should be understood that the shape of the waveguides does not generally have to be linear. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding and wave-coupling. Furthermore, waveguides that are placed side by side to achieve wave-coupling do not have to be placed side by side in a horizontal manner but can be placed in a top-down vertical manner or any other manner with respect to the horizontal substrate. Also, coupled

waveguides do not have to be exactly parallel or have the same widths as long as the desired effect of wave-coupling is achieved.

It should be understood that the force application point, part F **2308** can be at any location along the cantilever defined by points C **2303** and C' **2301**, and is not restricted to the exemplary location illustrated in device **2300**. It should be understood that this three-waveguide-gate device can be generalized to other multiple-waveguide gate devices by placing additional fixed or movable waveguides between waveguide A and B and oriented parallel to waveguides A and B so as to enable light to couple from waveguide A to waveguide B by coupling from waveguide A to these intermediate waveguides and then coupled back to waveguide B. As described below, this three gate device can also be implemented as a two gate device by taking away waveguide B, in which case the device functions as a phase shifter.

In an exemplary embodiment of device **2300** for operation at 800nm wavelength range, the wavelength λ can be at 820nm and the Waveguides A **2302**, B **2304**, and G **2322** can be implemented as the Waveguide **400** illustrated in FIG. 5A. In an exemplary embodiment of device **2300** for operation at 1500nm wavelength range, the wavelength λ can be at 1500nm and the Waveguides A **2302**, B **2304**, and G **2322** can be implemented as the Waveguide **400** illustrated in FIG. 5A.

In an exemplary embodiment for application to the 1500nm (or 1.5 μm) wavelength range, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. In an exemplary embodiment, the Waveguides A **2302** has width W_A equal to 0.4 μm, the Waveguide B **2304** has width W_B equal to 0.4 μm, and the Waveguide G **2322** has width W_G equal to 0.4 μm. At the "rest state" or "zero-force state" for which the force on part F **2308** is zero, the Waveguide A **2302** is located at an approximately parallel distance W_{gAG} of 0.3 μm from the Waveguide G **2322**, and the Waveguide G **2322** is in turn located at an approximately parallel distance W_{gGB} of 0.3 μm from Waveguide B **2304**. The material refractive indices of the Waveguides A, the Waveguide G, and the Waveguide B are denoted as n_A, n_B, and n_C,

respectively, and are taken to be $n_A=n_B=n_G=3.4$. These refractive indices give an effective planar-waveguide propagating refractive index of about 2 in a planar waveguide structure with a thickness of 0.25 μm. The material refractive index outside the waveguides is taken to be 1.5. In this exemplary embodiment for which the wavelengths of light are around a 1500nm range, ℓ'_C is about 15 μm. In this exemplary device, the force applying part F **2308** has dimension WF1 of 2 μm and WF2 of 10 μm. The midpoint of the area defining part F 2308 is approximately 10 μm from the mid point of waveguide G defined by the midpoint of the coupling length ℓ', and is approximately 25 μm away from the pivoted point C **2303**.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **2300** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **2300**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i)   General Operating Principle for the Device

The main action of the applied voltage preferably is to move Waveguide G **2322** either closer to or away from either Waveguide A **2302** or Waveguide B **2304**. The relative position of Waveguide G **2322** then affects the transfer of light from various inputs to various outputs. The general operation of the device can be illustrated via computer simulation of such light transfer as a function of the position of Waveguide G **2322**.

An exemplary operation of the device can be illustrated via the results of computer simulation as shown in FIGs. 19A and 19B. FIGs. 19A and 19B show the spatial distribution of the electric field strength for the light input at λ **2318** after propagating into waveguides A and B. The upper parts of FIGs. 19A and 19B are 2-D plots for which the brightness shows the relative field strength, and the lower parts of FIGs. 19A and 19B are 3-D plots for which the heights show the relative field strength. FIG. 19A shows the situation when

the applied voltage or force is zero. From FIG. 19A, it is evident that most of the energy of λ **2318** exits from Waveguide B **2304** at the port B2 **2314**. FIG. 19B shows the situation when a voltage is applied to create an electro-static force to move the center waveguide G down. From FIG. 19B, it is evident that most of the energy of λ **2318** exits from Waveguide A. FIG. 19A and FIG. 19B show the two representative interference flux patterns of light for the device, which is dependent on the state of the center waveguide G. In particular, one can switch between these two representative interference flux patterns of light by changing the state of the center waveguide G through the action of an applied voltage or applied mechanical force to move the center waveguide G away.

ii)   Exemplary Device 12 as a Switching Element

In a preferred and useful embodiment, the mechanical-optical phosistor **2300** operates as a switching element. In general, the mechanical-optical phosistor **2300** has one or more light inputs with associated wavelengths. In the zero-force state, for which there is zero force on part F **2308** of device **2300**, light at λ **2310** input into port A1 **2310** will result in a high power of light at λ **2320** exiting port B2 **2314** on Waveguide B **2304**, and a low power of light at λ **2316** exiting port A2 **2312** on Waveguide A **2302**.

In the applied-force state, for which there is nonzero force on part F **2308** of device **2300**, the gaps W_{gAG} and W_{gGB} will change due either to vertical or horizontal movements of waveguide G. As a result, the light power at λ **2318** exiting port B2 **2314** on Waveguide B **2304** will reduce eventually towards zero, and light power at λ **2316** exiting port A2 **2312** on Waveguide A **2302** will increase eventually to a maximum value when the movement is of the order of the gap size W_{gAG} or W_{gGB}.

If the applied force is induced by the voltages V1 and V2, the mechanical-optical phosistor **2300** can be used as a voltage-controlled optical switch to switch light energy between ports A2 **2312** and B2 **2314**.

The device has a symmetric property in that port B1 **2324** can play the role of a signal input port as in port A1 **2310**. In this case, port A2 **2312** (or B2 **2314**) will play the role of output port B2 **2314** (or A2 **2312**). Likewise, port A2 **2312** can play the role of the signal input port A1 **2310** and port B1 **2324** (or A1 **2310**) will then play the role of the signal output port B2 **2314** (or A2 **2312**). Lastly, port B2 **2314** can play the role of the signal input port A1 **2310** and port A1 **2310** (or B1 **2324**) will then play the role of the signal output port B2 **2314** (or A2 **2312**).

The above symmetric property of the device allows it to be used in particular as a 2x2 optical cross-bar switch. In this case, there will be a signal input at λ1 (signal 1) onto port A1 **2310** and another signal input at λ2 (signal 2—not shown in FIG. 18) into port B1 **2324**. The wavelength λ1 and λ2 can be the same or can be different for the two separate signal light beams (signal 1 and signal 2).

Depending on the state of the switch, it is possible to channel signal 1 to output port A2 **2312** and signal 2 to output port B2 **2314** or signal 1 to output port B2 **2314** and signal 2 to output port A2 **2312**. Specifically in the bar state output, corresponding to the applied-force state described above, signal input at λ1 in port A1 **2310** will propagate along Waveguide A **2302** and exit port A2 **2312** and signal input at λ2 in port B1 **2324** will propagate along Waveguide B **2304** and exit port B2 **2314**.

In the cross-state output, corresponding to the zero-force state described above, most of signal output at λ1 in port A1 **2310** will couple from Waveguide A **2302** to Waveguide B **2304** and exit port B2 and most of signal input at λ2 in port B1 **2324** will couple from Waveguide B **2304** to Waveguide A **2302** and exit port A2.

Hence, the net effect is that changing from the zero-force state to the applied-force state will bring the device from a cross-state output to a bar-state output. Operated in this fashion, the device is known to those skilled in the art as a 2x2 optical cross-bar switch, or more specifically in this case a 2x2 micro-electro-mechanical optical cross-bar switch. 2x2 cross-bar switches

can be mutually connected in such a way as to implement a MxN cross-bar switching in which signals input into M designated input ports can be channeled in any order to N output ports.

It should be understood that this description covers several but not all aspects of device performance. For example, it should be understood that the force on F **2308** can be applied to via an electrical force as described, but can also be applied to via other types of forces such as acoustic force, hydraulic force, or acceleration force. Such variations are described instructively with respect to device **2300** in this or in other useful embodiments and/or applications.

iii) Exemplary Device 12 as a Phase Shifter

As in the case of Device 10, by choosing coupling length ℓ'_c so that $\ell'' = 2\ell'_c$, light input into waveguide A will be coupled back to waveguide A, the net result of which is an additional optical phase shift, whose value will depend on how many intermediate waveguides are coupled to. Typically the phase shift will be in multiple number of π radians (or 180°). When the active medium is in the loss state, light will remain in waveguide A (i.e. there will be no coupling to other waveguides) and there will be no additional optical phase shift. In this way, Device 12 can function as an mechanical-optically controlled phase shifter. In this case, the presence of waveguide B is not essential and the device can function as a two-waveguide device.

iv). Exemplary Device 12 as a Wavelength Multiplexer/De-Multiplexer or Wavelength Selective Switch

In another useful embodiment of the device, the waveguide A, G, and B have unequal widths W_A, W_G, and W_B. As is well known to those skilled in the art, waveguide couplers with unequal waveguide widths will have strong wavelength sensitivity. In particular, when the active medium is in the transparency state, only certain wavelengths of light will couple maximally from waveguide A to waveguide B, thus allowing the device to act not only as

a switch but as a wavelength-selective switch. As an exemplary embodiment, the widths W_A and W_B can be equal to 0.4 μm and W_G can be equal to 0.6 μm. Except for the difference in the waveguide widths providing wavelength sensitivity, this embodiment of the device is otherwise functionally and operationally identical to the device 2300 and descriptions and comments relating to the device 2300 are generally applicable to this device.

v).   Resonator Configuration Device

It should be evident to those skilled in the art that the Resonator I/Resonator II configuration for device 12 would be topologically similar to three-gate implementation of Resonator I/Resonator II configuration of Device 2. In the resonator configuration, the resonator can be supported by a cantilever in place of waveguide G. The joint of the cantilever beam to the resonator can either be from the bottom or from the side of the resonator structure. Note that for joining to the side, the joint must be as small as possible to reduce scattering loss at the joint. The bottom-type joint will be ideal for disk shape resonators since the joint can be made to the center of the disk that will have little light energy to scatter. As in device 2, it should be understood that the Resonator I/Resonator II Configuration Devices are otherwise functionally and operationally identical to the device 2300 and descriptions and comments relating to the device 2300 are generally applicable to the Resonator I/Resonator II Configuration Devices.

vi) Comments on Fabrication Methods

The structure shown in FIG. 18 can be fabricated using the well-known methods in fabricating MEM (Micro Electro Mechanical) devices, which typically use a thin layer of semiconductor transfer onto a silicon dioxide SiO_2 (glass) surface, and use selective etching technique to etch the SiO_2 underlayer to form an overhang for the semiconductor structure. As an example, in FIG. 20, we show that beginning with a wafer made up of a thin layer of GaAs bonded to a SiO_2 substrate such as quartz. The GaAs thin layer

may have a thickness of 0.25μm, for example, which will form the thickness required for the waveguides. An optical (or e-beam) lithography is used to pattern the waveguide structures. FIG. 20A shows the situation after the patterning in which photoresist covers the area that will be etched. The wafer is then subjected to reactive-ion-beam etching of GaAs using chlorine chemistry, which is a typical semiconductor etching process. This etches the GaAs layer away as shown in FIG. 20B. The wafer is the dipped into a dilute hydrofluoric (HF) acid solution. The HF solution has a selective-etching property in that it will etch only the SiO_2 material and not the semiconductor GaAs material. This selective etching property allow us to undercut the materials under the GaAs thin film as shown in FIG. 20C. After the removal of photoresists with acetone, we will end up with an overhanging structure for the GaAs thin film. Those skilled in the art will know how to use such undercutting property to make the desired structure shown in FIG. 18 using the typical semiconductor fabrication processes.

F.   EXEMPLARY DEVICE 13 (A RELAYING GATE MECHANICAL-OPTICAL DEVICE)

FIG. 21 illustrates an exemplary device and a second general embodiment **2400** of a mechanical-optical phosistor device employing directionally coupled waveguides. For purposes of illustration and not limitation, the device is described according to one useful function as a switching element for slow or ultrafast optical pulses of sufficient energy and wavelength. The device **2400** is not limited to use as a switching element and can instead be used to implement other mechanical-optical device functions to perform in various applications. It can be utilized, for example, as a MxN optical cross-bar switch, a variable coupling device (including an optical loop mirror and a pulse storage ring), a mechanical-optical phase shifter, a resonator frequency tuning element, a light intensity modulator, a light intensity regulator, a micro-electro-mechanical optical switch, a micro-

acousto-mechanical optical switch, a micro-hydro-mechanical optical switch, and a variable optical attenuator. The device can be referred to as an "Mechanical-Optical Relaying-Gate Phosistor" (MO-RG Phosistor **2400**).

MO-RG Phosistor **2400** preferably includes a first pathway of light

5   consisting of the spatial region occupied by Waveguide A **2402**, a second pathway of light consisting of the spatial region occupied by Waveguide B **2404**, and a third Waveguide G **2422**. Waveguide G is suspended in air and is surrounded by bottom substrate area S **2470**, and areas A1 **2472**, A2 **2474**, and A3 **2476**, which are solid areas. Preferably, the Waveguide G **2422**

10   includes no active medium but can be moved physically or mechanically by placing it on a cantilever pivoted at C **2403** defined by the beam between points C **2403** and C' **2401**. Such mechanical motion can be induced, for example, by applying force on part F **2408** along the cantilever, where part F **2408** is shown to have a width WF1 and a length WF2. As described below,

15   switching action can be achieved either by moving the waveguide G **2422** vertically or by moving the waveguide G **2422** horizontally.

As an exemplary embodiment of the device **2400** which allows vertical movement of waveguide G **2422**, the force can be induced, for example, via applying voltage to a pair of parallel metal plate in which one of the metal

20   plates **2409** is attached to part F **2408** of the cantilever and another of the metal plates **2411** is situated on the substrate area below part F **2408**. Metal plate **2411** is oriented parallel to metal plate **2409** and is spaced by a distance P1 from the bottom on part F **2408**. Metal plate **2411** can have an irregular shape other than that shown as long as it is around the area or adjacent to the

25   area below part F **2408**. A voltage source **2406** having a variable voltage V1 can be applied across the parallel pair of metal plates **2409** and **2411** to move waveguide G in a vertical direction pivoted around point C **2403**. These forces on part F **2408** can also be induced via other mechanical means, for example, acoustically, hydraulically, or via acceleration. We may refer to this exemplary

30   embodiment as the vertical-motion embodiment of device **2400**.

Alternatively as an exemplary embodiment of the device **2400** which allows horizontal movement of waveguide G **2422**, the waveguide G **2422**

may be moved via a metal plate **2405** attached to part F **2408** but oriented vertically and a metal plate **2407** attached to area A1' **2473**. Metal plate **2407** is oriented parallel to metal plate **2405** but spaced by a distance P2 away from metal plate **2405**. These vertical pairs of metal plate **2405** and **2407** can

5   be used to move the cantilever horizontally (pivoted around point C **2403**) via applying a voltage V2 **2490** to the parallel metal plates **2405** and **2407**. These forces on part F **2408** can also be induced via other mechanical means, for example, acoustically, hydraulically, or via acceleration. We may refer to this exemplary embodiment as the horizontal-motion embodiment of device **2400**.

10   Similar device switching function can be achieved by using either the vertical-motion embodiment or the horizontal-motion embodiment of the device **2400**.

In an exemplary embodiment, the Waveguides A **2402**, B **2404**, and G **2422** can each be implemented as the Waveguide **400** illustrated in FIG. 5A.

15   Waveguides A, B, and G are support from below in areas A1, A2, and A3 by having the lower cladding region being solid materials such as silicon dioxides. The Waveguide A **2402** preferably includes an input port A1 **2410** and an output port A2 **2412**. The Waveguide B **2404** preferably includes an input port **2424** and an output port B2 **2414**. Waveguides A and B cross each

20   other at a cross junction D **2495**. **Waveguide G** 2422 preferably includes a shaped region **2328** that traces an area of the interface between waveguides A and B. FIG. 21 illustrates that Waveguide A **2402** has width W_A and is located at an approximately parallel distance (coupling gap or distance) W_{gAG} from Waveguide G **2422**, which has width W_G. The shaped

25   region **2328 of** Waveguide G **2422**, after making a $90°$ turn, is in turn located at an approximately parallel distance (coupling gap or distance) W_{gGB} from Waveguide B **2404**, which has width W_B.

The input port A1 **2410** on the Waveguide A **2402** is configured to receive light having wavelength λ (at λ) (SIGNAL IN λ) **2418**. In a useful

30   embodiment, this light at λ **2418** is continuous wave (CW) light. Depending on the state of the mechanical-optical phosistor **2400**, light can be output from the output port B2 **2414** as light having wavelength λ (at λ) (ON-SIGNAL OUT

λ) **2420**. In a useful embodiment, this light at λ **2420** is pulsed light. Light is also capable of being output from the output port A2 **2412** as light having wavelength λ (at λ) (OFF-SIGNAL OUT λ) **2416**. In a useful embodiment, this light at λ **2416** is pulsed light. Under certain operating conditions described below, most of the CW light at λ **2418** propagating along the Waveguide A **2402** will be transferred to Waveguide B **2404** through waveguide G **2422**. It should be understood that the light signals into and out of MO-RG Phosistor **2400** and other useful embodiments can include pulsed light signals, continuous wave (CW) light signals, or both, depending on which of the various operating modes of the embodiments are utilized in a particular application.

The coupling length $\ell_c|_{X-Y}$ is defined as the length at which a wave in a first waveguide (X) maximally couples into a second waveguide (Y) that is coupled to the first waveguide (X). As is known to those skilled in the art, the coupling length is a function of the gap distance between each pair of waveguides and the width of each waveguide. The gap distances can be chosen to achieve maximal coupling between waveguide X and waveguide Y.

In this device **2400**, the interaction length ℓ_A, defined as the length of interaction between waves in Waveguides A **2402** and G **2422**, and the interaction length ℓ_B, defined as the length of interaction between waves in Waveguides G **2422** and B **2404** extends to approximately the full coupling length ℓ_c so that $\ell_A = \ell_c|_{A-G}$ and $\ell_B = \ell_c|_{G-B}$ in one useful embodiment of the device, but may be different from $\ell_A = \ell_c|_{A-G}$ and $\ell_B = \ell_c|_{G-B}$ in other useful embodiments of the device. In the case of FIG. 21, the interaction length is defined geometrically by the length for which waveguides A and G, or G and B run closely parallel to each other.

It should be understood that the above dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the device **2400** and are not intended to limit other exemplary embodiments of any exemplary device, or the device **2400**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as

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the fabrication materials, processes or technologies that are employed. For

example, while the choice of $\ell_A = \ell_c |_{A-G}$ and $\ell_B = \ell_c |_{G-B}$ is illustrated in this

exemplary device, the interaction length may vary from the coupling length

$\ell_A = \ell_c |_{A-G}$ and $\ell_B = \ell_c |_{G-B}$ and still achieve similar device functions. Also,

the structure forming waveguide G does not have to be of the regular shape

shown. The overhanging of waveguide A and B is not necessary and

waveguides A and B can be adjacent to the edge of the hole or indentation

area.

Also, it should be understood that the shape of the waveguides do not

generally have to be linear. Curved shapes and different waveguide

dimensions may be utilized as long as they achieve the same functions such

as waveguiding and wave-coupling. Furthermore, waveguides that are placed

side by side to achieve wave-coupling do not have to be placed side by side

in a horizontal manner but can be placed in a top-down vertical manner or any

other manner with respect to the horizontal substrate. Also coupled

waveguides do not have to be exactly parallel or have the same widths as

long as the desired effect of wave-coupling is achieved. In addition,

Waveguide A and Waveguide B can be two independent waveguides and do

not have to cross each other. Furthermore, the turning of Waveguide G can

be any degree and does not have to be a right angle, as long as the required

wave-relaying effect of relaying wave from Waveguide A to Waveguide B

through Waveguide G is achieved.

It should be understood that the force application point, part F **2408**

can be at any location along the cantilever defined by points C **2403** and C'

2401, and is not restricted to the exemplary location illustrated in device **2400**.

It should be understood that this three-waveguide relaying-gate device can be

generalized to other multiple-waveguide gate devices by placing additional

fixed or movable waveguides between waveguide A and G (or G and B) and

oriented parallel to waveguides A and G (or G and B) so as to enable light to

couple from waveguide A to waveguide G (or G to B) by coupling from

waveguide A (or G) to these intermediate waveguides and then coupled back to waveguide G (or B).

In an exemplary embodiment of device **2400** for operation at 800nm wavelength range, the wavelength λ can be at 820nm and the Waveguides A **2402**, B **2404**, and G **2422** can be implemented as the Waveguide **400** illustrated in FIG. 5A. In an exemplary embodiment of device **2400** for operation at 1500nm wavelength range, the wavelength λ can be at 1500nm and the Waveguides A **2402**, B **2404**, and G **2422** can be implemented as the Waveguide **400** illustrated in FIG. 5A.

In an exemplary embodiment for application to the 1500nm (or 1.5 μm) wavelength range, the cross-sectional dimensions of the waveguide **400** are 0.4 μm wide by 0.25 μm thick. In an exemplary embodiment, the Waveguide A **2402** has width W_A equals to 0.4 μm, the Waveguide B **2404** has width W_B equals to 0.4 μm, and the Waveguide G **2422** has width W_G equal to 0.4 μm. At the "rest state" or "zero-force state" for which the force on part F **2408** is zero, the Waveguide A **2402** is located at an approximately parallel distance W_{gAG} of 0.4 μm from the Waveguide G **2422**, and the Waveguide G **2422** is in turn located at an approximately parallel distance W_{gGB} of 0.4 μm from Waveguide B **2404**. The material refractive indices of the Waveguides A, the Waveguide G, and the Waveguide B are denoted as n_A, n_B, and n_C, respectively, and are taken to be $n_A = n_B = n_G = 3.4$. These refractive indices give an effective planar-waveguide propagating refractive index of about 2 in a planar waveguide structure with a thickness of 0.25 μm. The material refractive index outside the waveguides is taken to be 1.5. In this exemplary embodiment for which the wavelengths of light are at around 1500nm range, $\ell_A = \ell_c \,|_{A-G}$ and $\ell_B = \ell_c \,|_{G-B}$ are both about 15 μm. In this exemplary device, the force applying part F **2408** has dimension WF1 of 2 μm and WF2 of 10 μm. The mid point of the area defining part F **2408** is approximately 20 μm from the mid point of waveguide G, and is approximately 25 μm away from the pivoted point C **2403**.

It should be understood that these dimensions, exemplary lengths, and geometry are presented for purposes of illustrating a useful embodiment of the devices **2400** and are not intended to limit other exemplary embodiments of any exemplary device, or the devices **2400**. A variety of dimensions, sizes, and geometry can be used, depending on the application desired as well as the fabrication materials, processes or technologies that are employed.

i)   General Operating Principle for the Device

The main action of the applied voltage preferably is to move Waveguide G **2422** either closer to or away from either Waveguide A **2402** or Waveguide B **2404**. The relative position of Waveguide G **2422** then affects the transfer of light from various inputs to various outputs. In particular, in the On state, waveguide G at its equilibrium position waveguide along Waveguide A **2402** will be transferred fully to Waveguide G **2422**. Waveguide G then curves around and relays the wave to Waveguide B **2404**. This causes the wave into port A1 to exit port B2, effectively turning 90^{0} about the junction **2495**. In the Off state, waveguide G is moved away (e.g. downwards vertically), and wave coupling from Waveguide A **2402** to Waveguide G **2422** is reduced or extinguished. This causes the wave entering A1 to exit port A2 by propagating through the junction **2495**.

ii)   Exemplary Device 13 as a Switching Element

In a preferred and useful embodiment, the mechanical-optical phosistor **2400** operates as a switching element. In general, the mechanical-optical phosistor **2400** has one or more light inputs with associated wavelengths. In the zero-force state, for which there is zero force on part F **2408** of device **2400**, light at λ **2410** input into port A1 **2410** will result in a high power of light at λ **2420** exiting port B2 **2414** on Waveguide B **2404**, and a low power of light at λ **2416** exiting port A2 **2412** on Waveguide A **2402**.

In the applied-force state, for which there is nonzero force on part F **2408** of device **2400**, the gaps W_{gAG} and W_{gGB} will change due either to vertical or horizontal movements of waveguide G. As a result, the light power

at λ **2418** exiting port B2 **2414** on Waveguide B **2404** will reduce eventually towards zero, and light power at λ **2416** exiting port A2 **2412** on Waveguide A **2402** will increase eventually to a maximum value when the movement is of the order of the gap size W_{gAG} or W_{gGB}.

5   If the applied force is induced by the voltages V1 and V2, the mechanical-optical phosistor **2400** can be used as a voltage-controlled optical switch to switch light energy between ports A2 **2412** and B2 **2414**.

As is known to those skilled in the art, these switches can be mutually connected in such a way as to implement a MxN cross-bar switching in which

10   signals input into M designated input ports can be channeled in any order to N output ports.

It should be understood that this description covers several but not all aspects of device performance. For example, it should be understood that the force on F **2408** can be applied to via an electrical force as described, but can

15   also be applied to via other types of forces such as acoustic force, hydraulic force, or acceleration force. Such variations are described instructively with respect to device **2400** in this or in other useful embodiments and/or applications.

iii).   Exemplary Device 13 as a Wavelength Multiplexer/De-

20   **Multiplexer or Wavelength Selective Switch**

In another useful embodiment of the device, the waveguide A, G, and B have unequal widths W_A, W_G, and W_B. As is well known to those skilled in the art, waveguide couplers with unequal waveguide widths will have strong wavelength sensitivity. In particular, when the active medium is in the

25   transparency state, only certain wavelengths of light will couple maximally from waveguide A to waveguide B, thus allowing the device to act not only as a switch but as a wavelength selective switch. As an exemplary embodiment, the width W_B and W_G can be equal to 0.6 μm and W_A can be equal to 0.4 μm. Except for the difference in the waveguide widths providing wavelength

30   sensitivity, this embodiment of the device is otherwise functionally and operationally identical to the device **2400** and descriptions and comments relating to the device **2400** are generally applicable to this device.

iv).   Resonator Configuration Device

A top view of a resonator configuration device is shown in FIG. 22. In the resonator configuration, the resonator can be supported by a cantilever in place of waveguide G. The joint of the cantilever beam to the resonator can either be from the bottom or from the side of the resonator structure. Note that for joining to the side, the joint must be as small as possible to reduce scattering loss at the joint. The bottom-type joint will be ideal for disk shape resonator as in that case the joint can be to the center of the disk that will have little light energy to scatter. As in device 2, it should be understood that the Resonator Configuration Devices are otherwise functionally and operationally identical to the device **2400** and descriptions and comments relating to the device **2400** are generally applicable to the Resonator Configuration Devices.

v) Comments on Fabrication Methods

The structure shown in FIG. 21 can be fabricated using the well-known methods in fabricating MEM (Micro Electro Mechanical) devices, which typically use a thin layer of semiconductor transfer onto a silicon dioxide SiO_2 (glassy) surface, and use selective etching technique to etch the SiO_2 underlayer to form an overhang for the semiconductor structure. As an example, in FIG. 20, we show that beginning with a wafer made up of a thin layer of GaAs bonded to a SiO_2 substrate such as quartz. The GaAs thin layer may have a thickness of $0.25\mu m$, for example, which will form the thickness required for the waveguides. An optical (or e-beam) lithography is used to pattern the waveguide structures. FIG. 20A shows the situation after the patterning for which one has photoresist covering the area that will be etched. The wafer is then subjected to reactive-ion-beam etching of GaAs using chlorine chemistry, which is a typical semiconductor etching process. This etches the GaAs layer away as shown in FIG. 20B. The wafer is the dipped

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into a dilute hydrofluoric (HF) acid solution. The HF solution has a selective-etching property in that it will etch only the SiO_2 material and not the semiconductor GaAs material. This selective etching property allow us to undercut the materials under the GaAs thin film as shown in FIG. 20C. After the removal of photoresists with acetone, we will end up with an overhanging structure for the GaAs thin film. Those skilled in the art will know how to use such undercutting property to make the desired structure shown in FIG. 21 using the typical semiconductor fabrication processes.

VIII. PHOSISTOR EXEMPLARY FABRICATION METHOD

Referring now to FIGs. 26A-26P described is an exemplary procedure for fabrication of the waveguide and active structures, such as the exemplary structures illustrated in FIGS. 5A, 5B, 5C, and 5D. This procedure is given for the purpose of illustration and not limitation, as there are other procedures which can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The phosistor-type device structure can be fabricated by epitaxial layer growth such as MOCVD (Metal-Organic Chemical Vapor Deposition) or MBE (Molecular-Beam Epitaxy), local area etching, re-growth, E-beam lithography, and nano-fabrication techniques. We take as an example, an InGaAsP based device with multiple quantum well as the active layer. An exemplary phosistor-type device typical of those discussed above is shown in FIG. 23A for which two waveguides, waveguide A **2502** and waveguide B **2504** with waveguide widths W_A and W_B, respectively, are placed parallel to each other spaced by a gap W_g for an interation length of ℓ. Waveguide B is occupied by an active medium section **2508** with length L. Other parts of waveguide A and B are transparent waveguides **2580**. In an exemplary device W_A=0.4μm, W_B=0.4μm, W_g=0.4μm, ℓ=15 μm, and L=15 μm.

The epitaxial layer structure for the active medium section **2508** is shown in FIG. 24 and it is made up of various layers of lattice matched In_1.

$_x$Ga$_x$As$_{1-y}$P$_y$ (in short-formed as InGaAsP) materials with compositions x and y chosen to give different bandgap wavelengths. Note that the bandgap wavelength λ_g specifies uniquely the compositions of x and y for lattice matching. The epitaxial layer structure shown in Fig. 24 is made up of a first layer **2620** of t$_1$ thick n-doped InGaAsP material with a bandgap wavelength of λ_{g1} and a n-dopant density of n$_1$ grown on a n-doped InP substrate **2610** with a substrate dopant density of n$_{sub}$. In an exemplary device, t$_1$=1.5μm, λ_{g1}=1.15μm, n$_1$=5x10^{17}/cm^3, and n$_{sub}$>10^{18}/cm^3. This first layer **2620** forms the lower waveguide cladding. The first layer is followed on top by a second layer **2630** of t$_2$ thick n-doped InP with a dopant density of n$_2$, which forms an etch-buffer layer useful for generating a regrowth surface to be described below. In an exemplary device, t$_2$=0.05 μm, and n$_2$=5x10^{17}/cm^3. A third layer **2640**, to be referred to as multiple-quantum-well waveguide core layer (or waveguide-core active layer), with a thickness of t$_3$ is then grown on top of the second layer **2630**. In an exemplary device t$_3$=0.243μm. This waveguide-core active layer **2640** is made up of a series of sub-layers forming the quantum-well active medium. The lowest part of layer **2640** begins with an undoped d$_{LG}$ thick InGaAsP layer **2642** with a bandgap wavelength of λ_{gLG}, which forms the lower part of the waveguide core. In an exemplary device λ_{gLG}=1.25 μm and d$_{LG}$=9nm. Sub-layer **2642** is then followed on top by 12 quantum well/barrier pairs for which each pair is made up of an undoped d$_{QWB}$ thick InGaAsP barrier layer **2644** with a bandgap wavelength of λ_{gQWB} and an undoped d$_{QW}$ thick InGaAs (i.e. y=0) quantum well layer **2646**. In an exemplary device λ_{gQWB}=1.25 μm. The upper-most part of layer **2640** is an undoped d$_{UG}$ thick InGaAsP layer **2648** with a bandgap wavelength of λ_{gUG}, which forms the upper-most part of the waveguide core. In an exemplary device λ_{gUG}=1.25 μm and d$_{UG}$=18nm. The waveguide core layer **2640** is followed on top by a fourth layer **2650** of t$_4$ thick p-doped InP with a dopant density of p$_4$, which forms the upper waveguide cladding. In an exemplary device t$_4$=1.5 μm and p$_4$=5x10^{17}/cm^3. The upper waveguide cladding layer **2650** is then followed by a fifth layer **2660** of t$_5$ thick highly p-doped InGaAsP layer with a bandgap

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wavelength of λ_{g5} and a dopant density of p_5 for the purpose of forming ohmic contact with metal. In an exemplary device, $t_5=30nm$, $p_5=1\times10^{18}/cm^3$, and $\lambda_{g5}=1.3$ µm. Metal M1 **2670** of thickness t_{m1} is deposited on top of layer **2660** to form an ohmic metal contact to the top n-type semiconductor. Metal M2 **2680** of thickness t_{m2} is deposited on the bottom of the n-doped substrate **2610** to form an ohmic contact to the bottom p-type semiconductor. In an exemplary device M1 is Ti/Pt/Au, M2 is AuGe/Ni/Au, $t_{m1}=0.2$µm, and $t_{m2}=0.2$µm.

The epitaxial layer structure for the transparent waveguide section **2580** is shown in FIG. 25. It is identical to the active medium section **2508** of FIG. 24 except that the waveguide core layer has no quantum wells. Specifically, it is made up of various layers of lattice matched $In_{1-x}Ga_xAs_{1-y}P_y$ (in short-formed as InGaAsP) materials with compositions x and y chosen to give different bandgap wavelengths. Note that the bandgap wavelength λ_g specifies uniquely the compositions of x and y for lattice matching. The epitaxial layer structure shown in Fig. 25 is made up of a first layer **2720** of t_1 thick n-doped InGaAsP material with a bandgap wavelength of λ_{g1} and a n-dopant density of n_1 grown on a n-doped InP substrate **2710** with a substrate dopant density of n_{sub}. In an exemplary device, $t_1=1.5$µm, $\lambda_{g1}=1.15$µm, $n_1=5\times10^{17}/cm^3$, and $n_{sub}>10^{18}/cm^3$. This first layer **2720** forms the lower waveguide cladding. The first layer is followed on top by a second layer **2730** of t_2 thick n-doped InP with a dopant density of n_2, which forms an etch-buffer layer useful for generating a regrowth surface to be described below. In an exemplary device, $t_2=0.05$ µm, and $n_2=5\times10^{17}/cm^3$. A third layer **2740**, to be referred to as waveguide core layer, with a thickness of t_3 is then grown on top of the second layer **2730**. In an exemplary device $t_3=0.243$µm. This waveguide-core active layer **2740** is made up of an undoped t_3 thick InGaAsP layer with a bandgap wavelength of λ_{g3}, which forms the waveguide core. In an exemplary device $\lambda_{g3}=1.25$ µm. The waveguide core layer **2740** is followed on top by a fourth layer **2750** of t_4 thick p-doped InP with a dopant density of p_4, which forms the upper waveguide cladding. In an exemplary device $t_4=1.5$

μm and $p_4=5 \times 10^{17}/cm^3$. The upper waveguide cladding layer **2750** is then followed by a fifth layer **2760** of t_5 thick highly p-doped InGaAsP layer with a bandgap wavelength of λ_{g5} and a dopant density of p_5.

The fabrication process is now described by Step 1 – 18 below:

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Step 1: Using the standard as MOCVD (Metal-Organic Chemical Vapor Deposition) or MBE (Molecular-Beam Epitaxy) III-V compound semiconductor growth technique, we first grow the t_1 thick 1st layer **2620/2720** (note that **2620** is the same as **2720**), the t_2 thick 2nd layer **2630/2630**, and the t_3 thick active

10 3rd layer **2640** on the n-doped InP substrate **2610/2710**. The above growth forms an active layer structure **2640** over the entire wafer. However, only some selected regions of the waveguide such as region **2308** are to have active material. This is achieved by patterning, masking, etching and regrowth technique, during which the wafer areas where we need the active material

15 (called the Active-Medium Areas) are blocked via the patterning and masking and are not etched away. The other areas (called the Transparent-Medium Areas) will be etched away and regrown with the transparent waveguide core structure of **2740**, which does not have the quantum wells.

20 Step 2: (See FIG. 26A) A 0.3μm thick SiO_2 mask layer is deposited on top of step 1 structure using the standard Plasma Enhanced Chemical Vapor Deposition (PECVD) technique familiar to those skilled in the art. The wafer is then spin-coated with a 200nm thick negative E-beam resist NEB-22. Pattern that will retain the active-medium area is then written by an electron beam on

25 the NEB-22 using a high-resolution electro-beam lithography machine such as Leica EBPG-4 e-beam direct writer. Such a pattern is shown by the dashed line area in figure 23B, which overlaps the intended active-medium area **2508** of Fig 23A shown as shaded region. Because NEB-22 is a negative E-beam resist, the area to be written by the electron beam is the same as the area to

30 be retained, which is the active-medium area. The unwritten region is then developed and dissolved away by NEB-22 developing chemicals. The net result is shown in FIG. 26A.

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Step 2: (see FIG. 26B) The pattern on NEB-22 is then transferred down to the silicon dioxide layer by etching away the SiO_2 region not covered by NEB-22 using the standard reactive-ion-beam etching (RIE) technique with CHF_3 plasma (e.g. 25 sccm CHF_3 at 30 mTorr pressure and 60W RIE RF power). The NEB-22 is then stripped away using NEB-22 stripping chemicals. This step is thus left with a SiO_2 pattern corresponding to the dashed line region in figure 23B. The SiO_2 pattern forms a hard mask for the subsequent etching of semiconductor in step 3. The net result is shown in FIG. 26B.

Step 3: (See FIG. 26C) The SiO_2 mask is used as an etching mask and a standard plasma etching technique that can retain submicron pattern transfer accuracy over the required etching depth is used to etch down the 3rd layer, which has a thickness of t_3. In an exemplary device, this etching depth is controlled to be slightly larger than the $t3=0.243\mu m$ etching depth required, such as between $0.243\mu m$ and $0.25\mu m$. A plasma etching technique suitable for this purpose is reactive-ion-beam etching using CH_4, H_2, Ar_2, gas mixture with a flow-rate ratio of 10:34:10 at 45 mTorr pressure and 90W RIE RF power. Another is using Inductively Coupled Plasma (ICP) etching technique with $Cl_2:N_2:Ar_2$ gas plasma with flow rates of 10:35:9 sccm (standard cubic foot per minute), respectively, under 140Watts ICP power, 345 V DC bias, 2.3 mTorr pressure, and 250 °C substrate temperature. This plasma etching process typically etches InGaAsP materials much faster than the SiO_2 mask and has a better than 10:1 etching rate differentiation between the etching of the InGaAsP semiconductor and the SiO_2 mask materials. After the etching, the region not etched away is still covered with the SiO_2 mask with a thickness of about 0.275 microns (some SiO_2 mask material of about 0.025 microns will be etched away with the semiconductor etching), which will be further used as a mask for the following regrowth step. The net result after the etching is shown in FIG. 26C.

Step 6: (See FIG. 26D) The above etching etches slightly into the 2nd layer of etch buffer layer, which is made up of InP. Using dilute 5% hydrochloric acid (HCl), it is possible to selectively etch away InP material without etching the

InGaAsP materials. Thus by dipping the wafer from step 5 into dilute HCl briefly, the etch buffer layer will be etched away, forming a smooth surface that stops at the top of the 1st layer, which is made up of InGaAsP material. The net result is shown in FIG. 26D. This smooth surface is conductive for the material regrowth to follow.

Step 7: (See FIG. 26 E) The wafer is then placed into the MBE or MOCVD machine for materials regrowth. A layer of material corresponding to layer 2 **2730** and layer 3 **2740** for the transparent waveguide structure of **2700** is regrown on the wafer. As materials growth will only occur on the lattice matched InGaAsP surface, the surface region still covered by the left-over SiO_2 mask will not have materials growth on top. After the materials growth, the SiO_2 mask is removed using buffer (i.e. dilute) hydrofluoric acid or by using RIE with CHF_3 gas. The resultant structure is shown in FIG. 26E.

Step 8: (See FIG. 26F) After removing the SiO2 mask, the wafer is sent for another epitaxial regrowth by MBE or MOCVD to grow the 4th layer **2650/2750**, and the 5th layer **2660/2760**. The resultant structure is shown in FIG. 26F.

Step 9: (See FIG. 26G) After the growth, the next step will be to etch the waveguide structure of FIG. 23A to form the waveguide A and waveguide B pattern. This is done again by using E-beam writing with NEB-22 and then transferring the pattern to an SiO_2 mask. The net result is shown in FIG. 26 G. This pattern is a cross section along the C-C' line in FIG. 23A.

Step 10: (See FIG. 26H) The patterning is followed by plasma etching of the InGaAsP semiconductor to a depth of larger than 3 micron (using the ICP process described in step 3). This depth is required to clear the entire epitaxial layer structure of FIGs. 24 and 25, so as to form a clear gap between waveguide A and waveguide B. The resultant structure is shown in FIG. 26H, where on the left is the transparent waveguide structure **2700** of Waveguide A

and on the right is the active-medium structure **2600** of Waveguide B. This resultant structure corresponds to the cross sectional structure along the C-C' line in FIG. 23A.

5   Step 11: (See FIG. 26I) The wafer is then planarized for metal contact. The planarization is achieved by spin-coating the wafer with Benzocyclobutene (BCB). As the waveguide is submicron in width, care has to be taken to reduce stress to the waveguides due to the BCB material, which may break or distort the waveguide. To reduce stress, first a 1 micron thick SiO2 layer is

10   deposited using PECVD before planarizing the wafer with BCB. The BCB is then baked. The stress induced by the BCB is relieved as the SiO_2 layer protects the waveguide from being pushed or pulled by the shrinking BCB during the baking process. The resultant structure is shown in FIG. 26I.

15   Step 12 (See FIG. 26J): The BCB coated is then etched down to the surface level of the waveguide. The BCB etching is done using the typical RIE process known to those skilled in the art, which involves the using of oxygen plasma to etch away polymeric materials. The resultant structure is shown in FIG. 26J.

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Step 13 (See FIG. 26K): The SiO_2 deposited on the top as well as the side of the waveguide is then removed by dipping the wafer into a buffer HF (BHF) solution. The resultant structure is shown in FIG. 26K.

25   Step 14 (See FIG. 26L): The void region between the waveguide and the BCB made by the BCB shrinkage and the removal of SiO_2 is subsequently filled with a second deposition of SiO_2 and BCB planarization. The resultant structure is shown in FIG. 26L.

30   Step 15 (See FIG. 26M): After that, an e-beam lithography process with NEB-22 is used to pattern the require opening for metal deposition. Before the e-beam lithography, the wafer is coated with a 0.3μm thick SiO_2 to be used as a

mask for the subsequent etching of BCB. The pattern required is shown in FIG. 23C in which the dotted line shows the required pattern, which overlaps the active-medium area **2508**. The net result after the transferring of the pattern to the SiO_2 mask layer is shown in FIG. 26M.

Step 16 (See FIG. 26N): After the patterning, the BCB in the exposed area is etched down using the typical RIE process known to those skilled in the art, which involves the using of oxygen plasma to etch away polymeric materials. The resultant structure is shown in FIG. 26N.

Step 17 (See FIG. 26O): After the BCB etching, the SiO_2 in the exposed area is etched down using the RIE process described in Step 2. The SiO_2 is etched down to just below the top of the 5th InGaAsP layer **2660** for Ohmic contact. The resultant structure is shown in FIG. 26O.

Step 18 (See FIG. 26P): After the BCB opening is made, photoresist is spin-coated on the wafer and patterned with the required metal contact pattern shown by the dotted line area in FIG. 23C. A 0.2µm thick Ti/Pt/Au metal layer is deposited and lifted off to form the p-side contact and a 0.2µm thick AuGe/Ni/Au metal layer is deposited on the back of the substrate to form the n-side contact. The resultant structure just before the top metal lift-off is shown in FIG. 26P. After the top metal lift-off, the metal m1 above the photoresist shown is lifted away. In this resultant structure, metal m1 will only make contact with the active-medium area **2508** in Waveguide B. This step completes the entire fabrication process.

In view of the wide variety of embodiments to which the principles of the invention can be applied, it should be understood that the illustrated embodiments are exemplary only, and should not be taken as limiting the scope of the present invention.

Of course, it should be understood that a wide range of changes and modifications can be made to the preferred exemplary embodiments described above. Thus, it is intended that the foregoing detailed descriptions

be regarded as illustrative rather than limiting, and that it be understood that it is the following claims, including all equivalents, which are intended to define the scope of this invention.

5   The claims should not be read as limited to the described order or elements unless stated to that effect. Therefore, all embodiments that come within the scope and spirit of the following claims and equivalents thereto are claimed as the invention.

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CLAIMS

1.   A light transfer device comprising:

a first light pathway having a first input and a first output;

a second light pathway having a second output, said second light pathway coupled to said first light pathway, wherein light from said first input is transferable between said first and second light pathways; and

an active medium positioned along at least one of said first and second light pathways, wherein said active medium is capable of receiving optical energy that modifies said active medium so that said active medium controls the transfer of light between said first and second light pathways.

2.   The device of claim 1 wherein said active medium may be modified so that at least a portion of the light from said first input remains on said first light pathway and is output from said first output of said first light pathway

3.   The device of claim 2 wherein said active medium is positioned between said first input and said first output and said active medium may be modified to a gain state upon receiving an amount of optical energy so that light from said first input of said first light pathway is amplified in said active medium

4.   The device of claim 3 wherein when said active medium is modified to a gain state, the effect on the transferability of the light to said second output of said second light pathway is not substantially affected.

5.   The device of claim 1 further comprising at least a third light pathway interposed between said first and second light pathways, said third light pathway configured in a circuitous shape to function as an intensity-increasing resonator between said first and second light pathways.

6.   The device of claim 5 wherein said third light pathway further comprises a ring-shaped waveguide.

7.   The device of claim 1 wherein said active medium further comprises a plurality of quantum wells within a waveguide.

8.   The device of claim 1 wherein said active medium further comprises a layer of material within which the potential energy of an electron is less than outside the layer and the motion of an electron perpendicular to said layer is quantized.

9.   The device of claim 8 wherein the thickness of said medium is between about 1 and 20 nanometers.

10.   The device of claim 1 wherein the distance between said first input and said first output is less than about 150 microns.

11.   The device of claim 1 wherein said pathways of said directional coupler are fabricated onto a substrate.

12.   The device of claim 1 wherein said first light pathway and said second light pathway comprise a multi-mode interference structure.

13.   The device of claim 1 wherein said first light pathway and said second light pathway comprise a photonic bandgap structure.

14.   The device of claim 2 wherein said active medium is positioned along said second light pathway and said active medium may be modified to a loss state upon receiving an amount of optical energy so that light from said first input of said first light pathway is absorbed in said active medium.

15.   The device of claim 2 wherein said active medium is positioned along said second light pathway and said active medium may be modified to a

gain state upon receiving an amount of optical energy so that light from said first input of said first light pathway is amplified in said active medium.

16.   The device of claim 1 wherein said active medium is positioned between the said first input and said first output and a portion of the light from said first input remains on said first light pathway and is output from said first output when the active medium is modified to a state of transparency.

17.   The device of claim 16 wherein said active medium may be modified to a loss state upon receiving an amount of optical energy so that the light energy output from said first output is decreased.

18.   The device of claim 1 wherein said active medium may be modified to a loss state having absorbtive properties so that the transferability of the light from said first input of said first light pathway to said second output of said second light pathway is affected by absorption by the medium.

19.   The device of claim 1 wherein said active medium may be modified to a gain state having amplification properties so that the transferability of the light from said first input of said first light pathway to said second output of said second light pathway is affected by amplification by the medium.

20.   The component of claim 1 wherein the refractive index of said active medium is substantially not changed upon modifying said medium.

21.   A light transfer device comprising:
    a first light pathway having a first input and a first output;
    a second light pathway having a second output, said second light pathway coupled to said first light pathway, wherein light from said first input is transferable between said first and second light pathways;
    a third light pathway interposed between said first and second light pathways, said third light pathway configured in a circuitous shape to function

as an intensity-increasing resonator between said first and second light pathways; and

an active medium positioned along at least one of said first, second, and third light pathways, wherein said active medium is capable of receiving light that modifies said active medium so that said active medium controls the transfer of light between said first, second and third pathways.

22. The device of claim 21 wherein said active medium may be modified so that at least a portion of the light from said first input remains on said first light pathway and is output from said first output of said first light pathway.

23. The device of claim 21 further comprising at least a fourth light pathway coupled to one or more of said first, second and third pathways, said fourth light pathway configured in a circuitous shape to function as an intensity-increasing resonator.

24. The device of claim 21 wherein said third light pathway further comprises a ring-shaped waveguide.

25. A logic device comprising:

a plurality of directional couplers, said directional couplers each being capable of modifying the propagation direction of a photon beam through an active medium having light transfer control properties modifiable via optical energy, said directional couplers being linked by inputs and outputs capable of transmitting said photon beam through one or more switchable propagation paths.

26. The logic device of claim 25 wherein said light transfer control properties of said active medium are modifiable without modifying substantially the refractive index of said active medium.

27. The logic device of claim 25 wherein said light transfer control properties alter the interference flux pattern of light within said logic device due to said active medium being in a loss state.

28. The logic device of claim 25 wherein said light transfer control properties alter the interference flux pattern of light within said logic device due to said active medium being in a gain state.

29. The logic device of claim 25 wherein each of said directional couplers further comprises:

at least a first input signal port capable of receiving said photon beam;

an active medium positioned near the first input signal port, wherein the active medium is capable of receiving electrical energy and said medium is drivable to a gain state by the electrical energy, and wherein the active medium is otherwise drivable to a transparency state; and

a first output port capable of transmitting a photon beam from the active medium, wherein the photon beam will be amplified when the active medium is in the gain state and of negligible energy when the active medium is in the transparency state.

30. The logic device of claim 29 wherein said light transfer control properties of said active medium are modifiable without modifying substantially the refractive index of said active medium.

31. A light transfer device comprising:

a first light pathway having a first input and a first output;

a second light pathway having a second output, said second light pathway coupled to said first light pathway, wherein light from said first input is transferable between said first and second light pathways; and

an active medium positioned along at least one of said first and second light pathways, wherein said active medium is capable of receiving

electrical energy that modifies said active medium so that said active medium controls the transfer of light between said first and second light pathways.

32.   The device of claim 31 wherein said active medium may be modified so that at least a portion of the light from said first input remains on said first light pathway and is output from said first output of said first light pathway.

33.   The device of claim 32 wherein said active medium is positioned between said first input and said first output and said active medium may be modified to a gain state by electrical energy so that light from said first input of said first light pathway is amplified in said active medium.

34.   The device of claim 33 wherein when said active medium is modified to a gain state, the effect on the transferability of the light to said second output of said second light pathway is not substantially affected.

35.   The device of claim 31 further comprising at least a third light pathway interposed between said first and second light pathways, said third light pathway configured in a circuitous shape to function as an intensity-increasing resonator between said first and second light pathways.

36.   The device of claim 35 wherein said third light pathway further comprises a ring-shaped waveguide.

37.   The device of claim 31 wherein said active medium further comprises a plurality of quantum wells within a waveguide.

38.   The device of claim 31 wherein said active medium further comprises a layer of material within which the potential energy of an electron is less than outside the layer and the motion of an electron perpendicular to said layer is quantized.

39.   The device of claim 38 wherein the thickness of said medium is between about 1 and 20 nanometers.

40.   The device of claim 31 wherein the distance between said first input and said first output is less than about 150 microns.

5   41.   The device of claim 31 wherein said pathways of said directional coupler are fabricated onto a substrate.

42.   The device of claim 31 wherein said first light pathway and said second light pathway comprise a multi-mode interference structure.

43.   The device of claim 31 wherein said first light pathway and said second light pathway comprise a photonic bandgap structure.

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44.   The device of claim 31 wherein the electrical energy comprises an applied electric field.

45.   The device of claim 31 wherein the electrical energy comprises an injection current.

15   46.   The device of claim 31 wherein the gain property of the active medium is modifiable via the use of a pn junction.

47.   The device of claim 31 wherein the loss property of the active medium is modifiable via the use of the quantum-confined Stark effect.

48.   The device of claim 31 wherein the loss property of the active

20   medium is modifiable via the use of the Franz-Keldysh effect.

49.   The device of claim 32 wherein said active medium is positioned along said second light pathway and said active medium may be modified to a loss state by an electrical energy so that light from said first input of said first light pathway is absorbed in said active medium.

50.   The device of claim 32 wherein said active medium is positioned along said second light pathway and said active medium may be modified to a gain state by an electrical energy so that light from said first input of said first light pathway is amplified in said active medium.

51.   The device of claim 31 wherein said active medium is positioned between the said first input and the said first output and a portion of the light from said first input remains on said first light pathway and is output from said first output when the active medium is modified to a state of transparency.

52.   The device of claim 51 wherein said active medium may be modified to a loss state by electrical energy so that the light energy output from said first output is decreased.

53.   The device of claim 31 wherein said active medium may be modified to a loss state having absorbtive properties so that the transferability of the light from said first input of said first light pathway to said second output of said second light pathway is affected by absorption by the medium.

54.   The device of claim 31 wherein said active medium may be modified to a gain state having amplification properties so that the transferability of the light from said first input of said first light pathway to said second output of said second light pathway is affected by amplification by the medium.

55.   The component of claim 51 wherein the refractive index of said active medium is substantially not changed upon modifying said medium.

56.   A light transfer device comprising:
a first light pathway having a first input and a first output;
a second light pathway having a second output, said second light pathway coupled to said first light pathway, wherein light from said first input is transferable between said first and second light pathways;

a third light pathway interposed between said first and second light pathways, said third light pathway configured in a circuitous shape to function as an intensity-increasing resonator between said first and second light pathways; and

an active medium positioned along at least one of said first, second, and third light pathways, wherein said active medium is capable of receiving electrical energy that modifies said active medium so that said active medium controls the transfer of light between said first, second and third pathways.

57.   The device of claim 56 wherein said active medium may be modified so that at least a portion of the light from said first input remains on said first light pathway and is output from said first output of said first light pathway.

58.   The device of claim 56 further comprising at least a fourth light pathway coupled to one or more of said first, second or third pathways, said fourth light pathway configured in a circuitous shape to function as an intensity-increasing resonator.

59.   The device of claim 56 wherein said third light pathway further comprises a ring-shaped waveguide.

60.   A light transfer device comprising:

a first light pathway having a first input and a first output;

a second light pathway having a second output, said second light pathway spaced from said first light pathway;

a third light pathway spaced from said first light pathway and said second light pathway, said third light pathway being movable between at least a first position relatively near both of said first and second light pathways and a second position relatively far from said first and second light pathways,

wherein said first position allows said first light pathway to be optically coupled with said third light pathway, and simultaneously allows said third light pathway to be optically coupled with said second light pathway.

61.   The device of claim 60 wherein said first, second and third light pathways include coupling sections that are relatively parallel to each other and said third light pathway being movable between said first and second light pathways.

62.   The device of claim 60 wherein said third light pathway includes an angled portion that is shaped to complement a side portion of said intersecting first and second light pathways, said angled portion of said third light pathway being movable toward and away from said intersecting point to allow light to be transferred between said first and second light pathways and said angled portion of said third light pathway.

63.   The device of claim 60 wherein said third light pathway includes two separate portions that are parallel to a portion of said first light pathway and a portion of said second light pathway, said third light pathway being movable toward and away from said first light pathway and said second light pathway to allow light to be transferred between said first and second light pathways and said third light pathway.

64.   A method of manufacturing a light transfer device, said method comprising the steps of:

etching at least two waveguide structures onto a substrate material, said waveguides each including input and output ends, at least one of said waveguides defining a gap area between its input and output end; and

integrating an active medium onto said substrate into said gap area using epitaxial layer forming techniques to define an active medium section of said one of said waveguides, said active medium section including a plurality of quantum wells.

65.   A method of manufacturing a waveguide structure, said waveguide structure having at least two waveguides, comprising:

providing a silicon dioxide substrate;

bonding a layer of GaAs to the substrate;

patterning a photoresist for the waveguide structure;

etching the GaAs not covered by the photoresist; and

etching the silicon dioxide structure so as to form an undercut.

66. The method of manufacturing of Claim 65, wherein at least one of the waveguide structures defines a gap area between an input and an output end, said gap manufactured by a method comprising:

providing an n-doped InP substrate;

epitaxially growing a lower cladding layer of n-doped InGaAsP onto said substrate;

growing a first layer of n-doped InP atop the lower cladding layer;

growing an undoped layer of InGaAsP atop the first layer of InP; and

providing a plurality of quantum wells, each quantum well comprising at least two layers, wherein a first barrier layer is provided by growing an undoped InGaAsP layer and a second quantum well layer is provided by growing an undoped layer of InGaAs.

67. A method of manufacturing a waveguide structure according to Claim 65, further comprising:

providing an n-doped InP substrate;

epitaxially growing a lower cladding layer of n-doped InGaAsP onto said substrate;

growing a first layer of n-doped InP atop the lower cladding layer;

growing an undoped layer of InGaAsP atop the first layer of InP; and

growing an upper cladding layer of p-doped InGaAsP and an upper layer of p-doped InGaAsP.

FIG. 1

(Prior Art)

F I G. 2A

F I G. 2 B

F I G. 2 C

FIG. 3A

FIG. 3B

FIG. 3C

Case A

$\lambda 1$ ... 310 ... 312 ... $\lambda 2$

326 ... e_1 302 ... 304 ... e_2 ... 328

314 ... 316

Loss at $\lambda 1$
Loss at $\lambda 2$

FIG. 4A

Case B

304 ... e_2 ... e_2

$\lambda 1$ ... $\lambda 2$

326 ... e_1 ... 302 ... $e_1 e_2$ ... 328

Gain at $\lambda 1$

FIG. 4B

Case C

$\lambda 1$ ... $\lambda 2$

326 ... 328

e_2

Transparency at $\lambda 1$
Loss at $\lambda 2$

FIG. 4C

Case D

304 ... e_2 ... 302

$\lambda 1$ ... $\lambda 2$

326 ... e_1 ... 328

e_2

Gain at $\lambda 1$
Transparency at $\lambda 2$
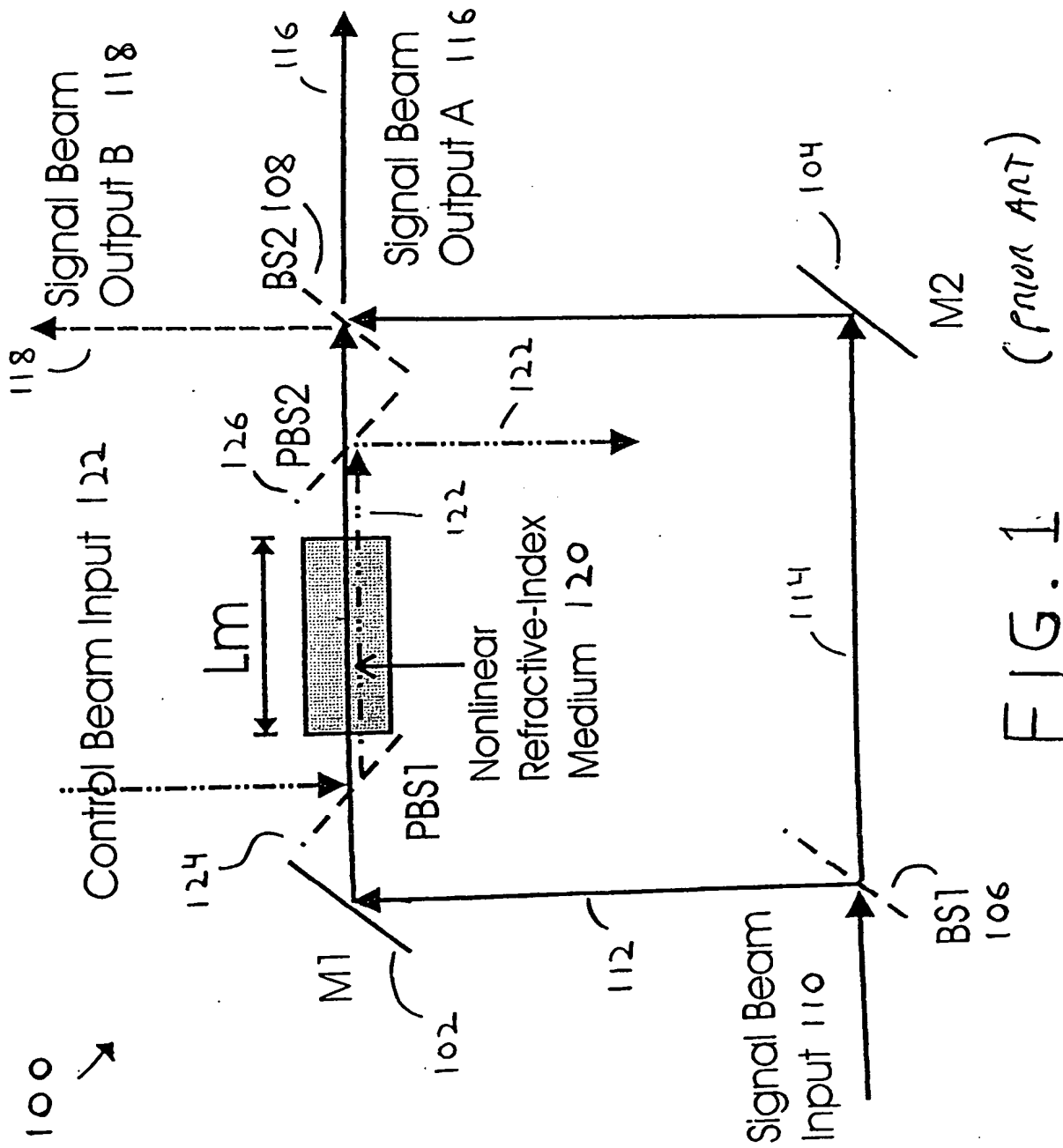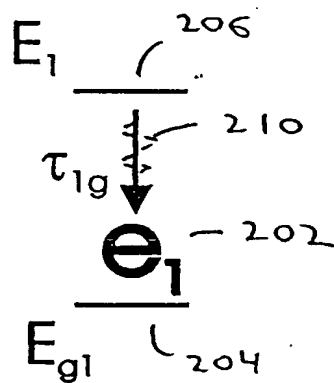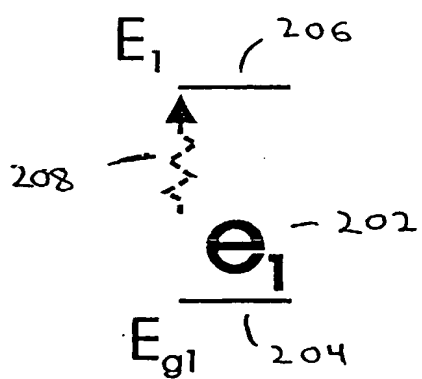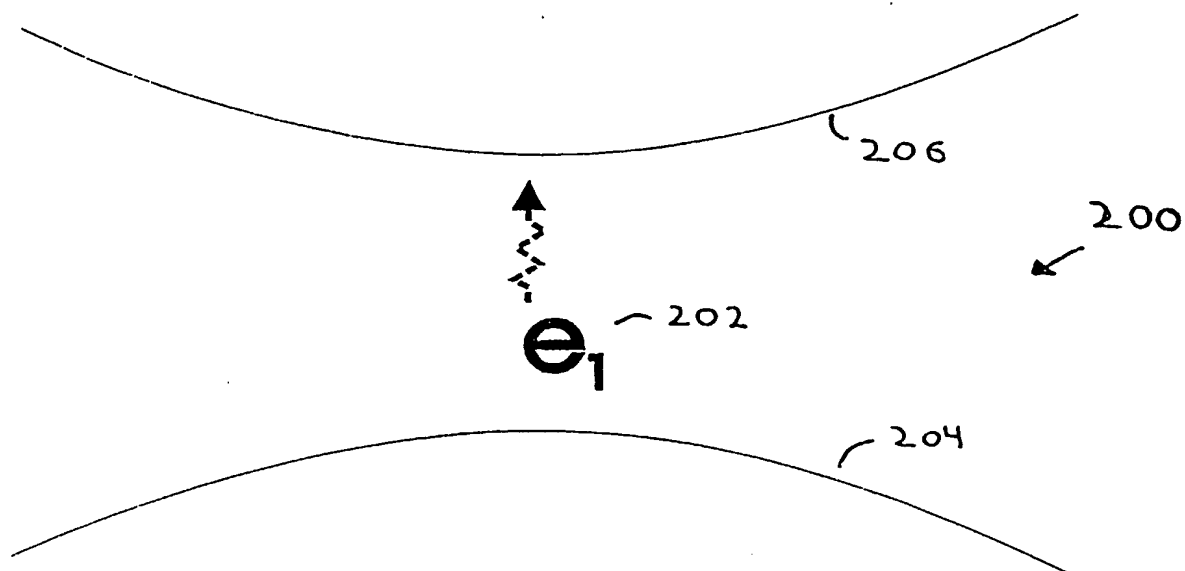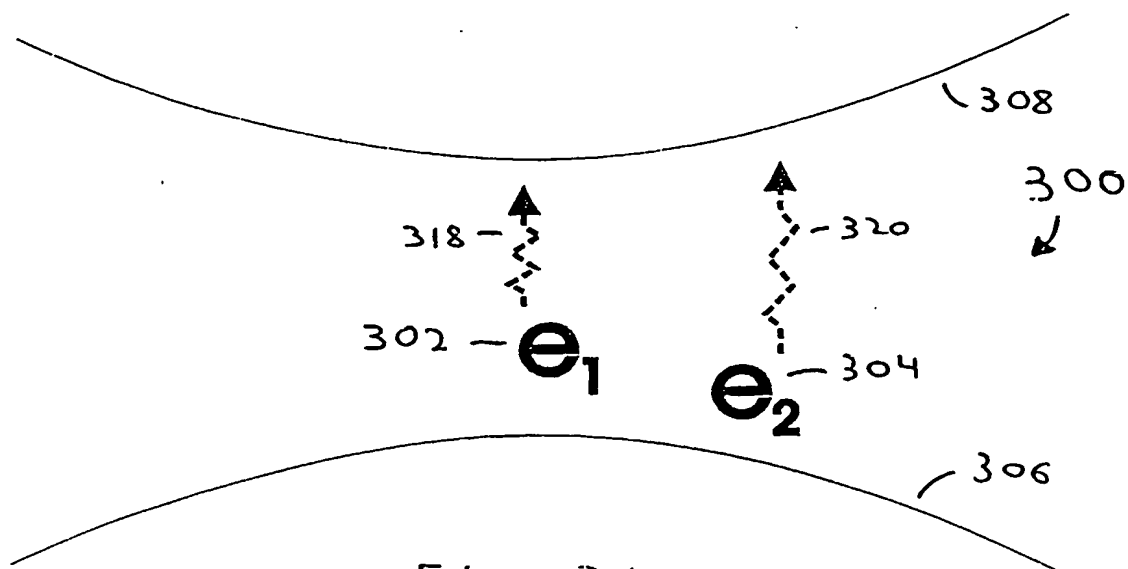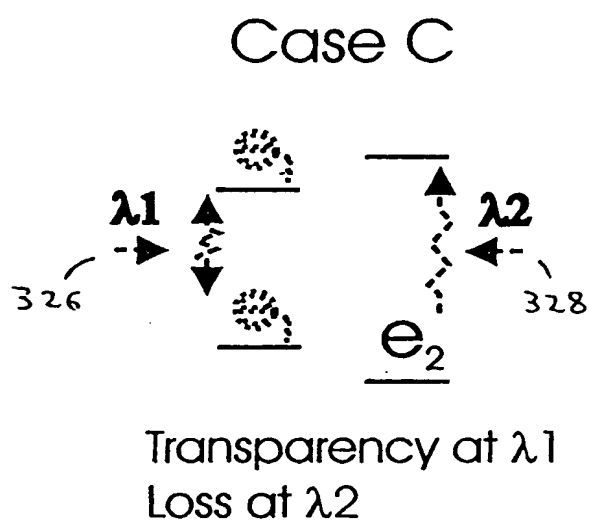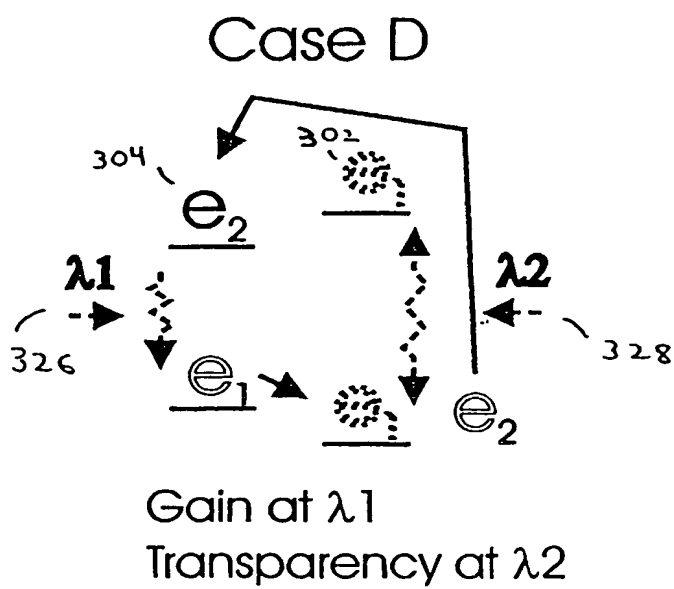
FIG. 4D

Case E
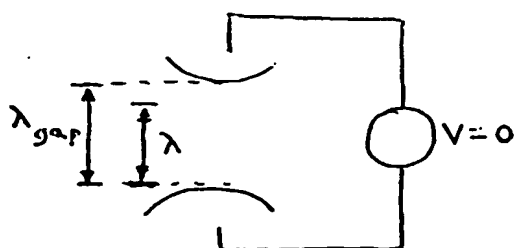
Transparency at λ

$V = 0$

$\lambda > \lambda_{gap}|_{V=0}$

FIG.4E

Case F
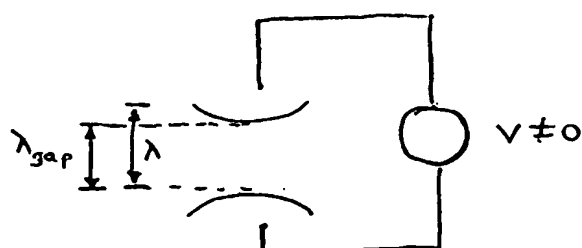
Loss at λ

$V \neq 0$

$\lambda < \lambda_{gap}|_{V \neq 0}$

FIG.4F

Case G
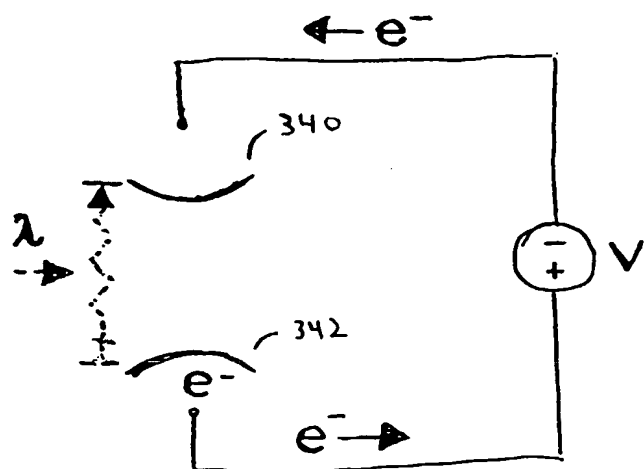
Loss at λ $(I_\lambda < I_{SAT})$

$0 < V < V|_{c = c_t(\lambda)}$

$c < c_t(\lambda)$

$\lambda > \lambda_{gap}$

FIG.4G

Case H
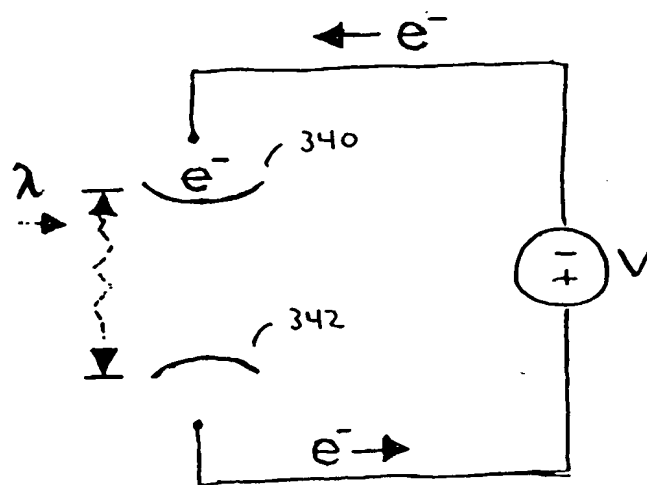
Transparency at λ

$0 < V = V|_{c = c_t(\lambda)}$

$c = c_t(\lambda)$

$\lambda > \lambda_{gap}$

FIG. 4H

$\leftarrow e^-$

340

λ

342

e^-

$\ominus\atop\oplus$ V

$e^- \rightarrow$

Transparency at λ $(I_\lambda \geqslant I_{SAT})$

$0 < V < V|_{c=c_t(\lambda)}$

$<< c_t(\lambda)$

$\lambda > \lambda_{gap}$

FIG. 4I

$\leftarrow e^-$

λ

$e^- \; 340$

342

$\ominus\atop\oplus$ V

$e^- \rightarrow$
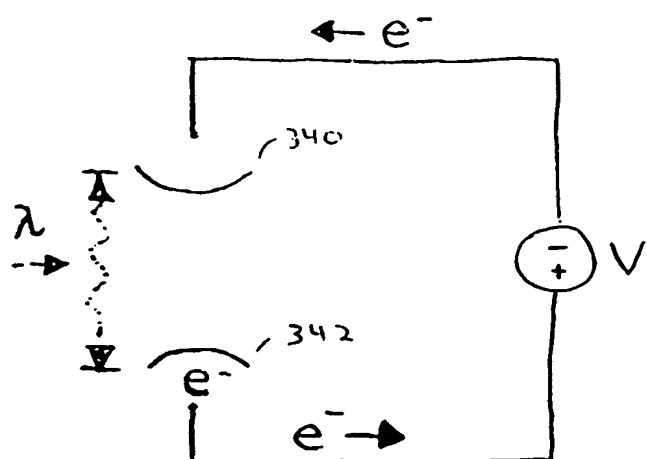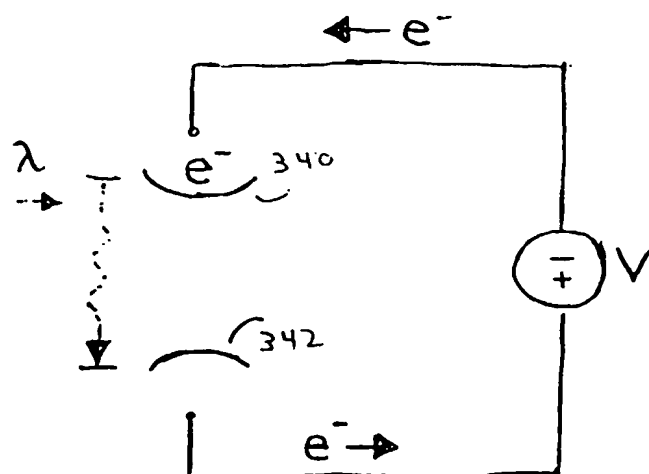
Gain at λ

$0 < V|_{c=c_t(\lambda)} < V$

$c > c_t(\lambda)$

$\lambda > \lambda_{gap}$

FIG. 4J

Case K

$e^- \rightarrow$

340

λ

342

$\ominus\atop\oplus$ V < 0

$\leftarrow e^-$

Loss at λ

$V < 0$

$\lambda > \lambda_{gap}$

FIG. 4K

FIG 5A

FIG. 5B

FIG. 5C

FIG. 5D

FIG. 6A

FIG. 6B

518

513

[A Pin 1]
510

[A Sout 1], 511   (Waveguide A)

[BPout 1], 514   (Waveguide B.)

520

518

[A Pin 1],
510

513

[A Sout 1], 511

[BPout 1], 514

520

Fig. 6C-1

[A Pin 1]
510

518

[AS out 1], 511

(Waveguide A).

513

[B Pout 1], 514

(Waveguide B)

520

518

[A Pin 1]
510

513

[AS out 1], 511

[B Pout 1], 514

520

Fig. 6C-2

[A Pin 1] 510
518
[A Sout 1], 511 (Waveguide A)
513
[B Pout 1], 514 (Waveguide B)
520

[A Pin 1] 510
518
513
[A Sout 1], 511
[B Pout 1], 514
520

Fig. 6C-3

FIG. 6C-4

Fig. 6D

i 518

Pin 1]
510

M513
[AS out 2], M511 (Arm A).

[B Pout 1], M514 (Arm B)
M520

1Pin 9] M518
510

M513
[AS out 9], M511

[B Pout 1], M514
M520

Fig. 6 E-1

Fig. 6 E-2

RS00

CW PWR
IN λ1
(APin1)

RS18

RS10

W_A

RS02 (WAVEGUIDE A

RS08

L

RS13
→

RS06

RS24

RS16

SIGNAL
IN λ2
(ASin2)

RS22

RS26

SIGNAL
OUT λ1
(AScut1b)

RS28
→

Wg₁

EASout 27, RS11

closed-loop
resonator RS17

waveguide B'
RS15

Wg₂

Waveguide B - RS04

RS14

(BPout1)
CW PWR
BYPASS
OUT λ1

RS20

(ASout1a)
SIGNAL
OUT λ1
RS12

Fig. 6F-1

Fig. 6F-2

Fig. 6F-3

RMG500

RMG S18

CW PWR
IN λ1 ----▶
(APin1)

RMG S10

closed-loop
resonator
RMG S17

WA

WAVEGUIDE A

L

I

RMG S08

RMG S13

SIGNAL
IN λ2
(ASin2)

RMG S22

RMG S26

SIGNAL
OUT λ1
(ASout λ6)

RMG S56
RMG S2';

RMG S28

[ASout 1],
RMG S11

closed-loop
resonator
RMG S21

RMG S12

(ASout1]
SIGNAL
OUT λ1

Waveguide B'

Wc1

λ1

λ1

λ1

Wg3

λ1

λ1

Wc4

λ1

λ1

Waveguide B

RMG S04

Wc2

closed-loop
resonator
RMG S15

(BPout1)
CW PWR
BYPASS
OUT λ1

RMG S14

RMG S20

Fig. 6f-4

FIG. 6F-5

FIG. 6 F - 6

FIG 6F-7

FIG. 6F-8

Fig. 6G-1

Fig. 66-2

Fig. 66-3

FIG. 7

[AP in 2], 610
618

[AS out 2], 612 (Waveguide A)
628

[BP out 2], 614 (Waveguide B)
620

[AP in 2], 610
618

[AS out 2], 612
628

[BP out 2], 614
620

Fig. 7A-1

[AP in 2], 610
618

[ASout 2], 612 (Waveguide A)
628

[BPout 2], 614   (Waveguide B)
620

[AP in 2], 610
618

[ASout 2], 612
628

[BPout 2], 614
620
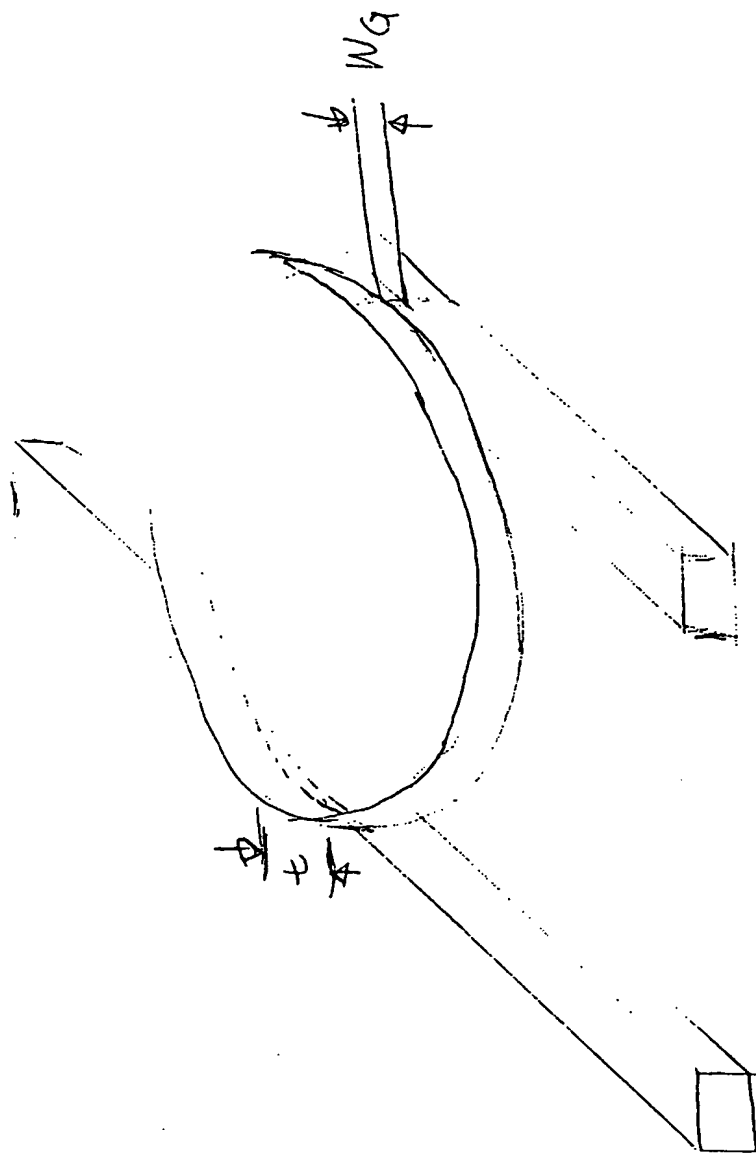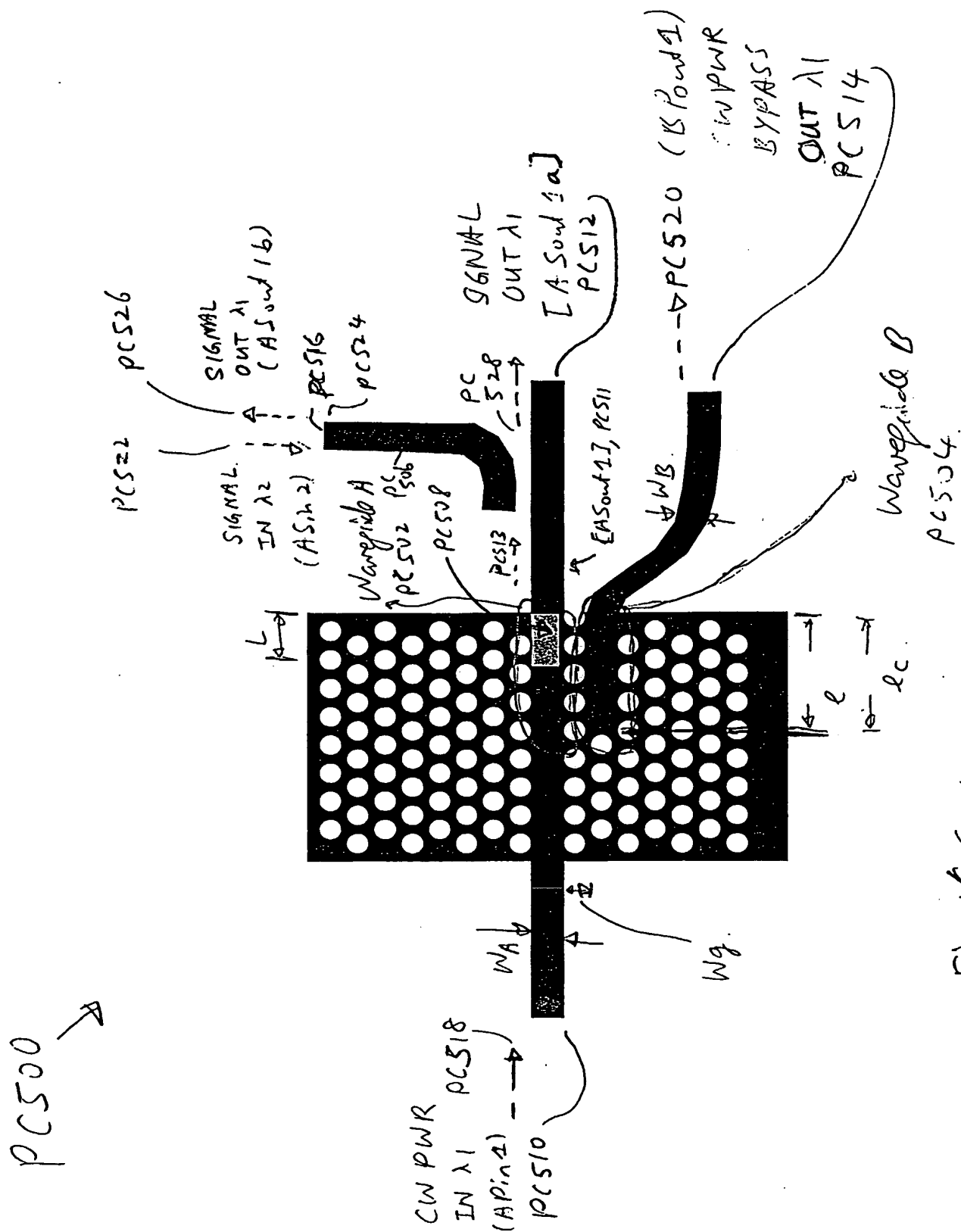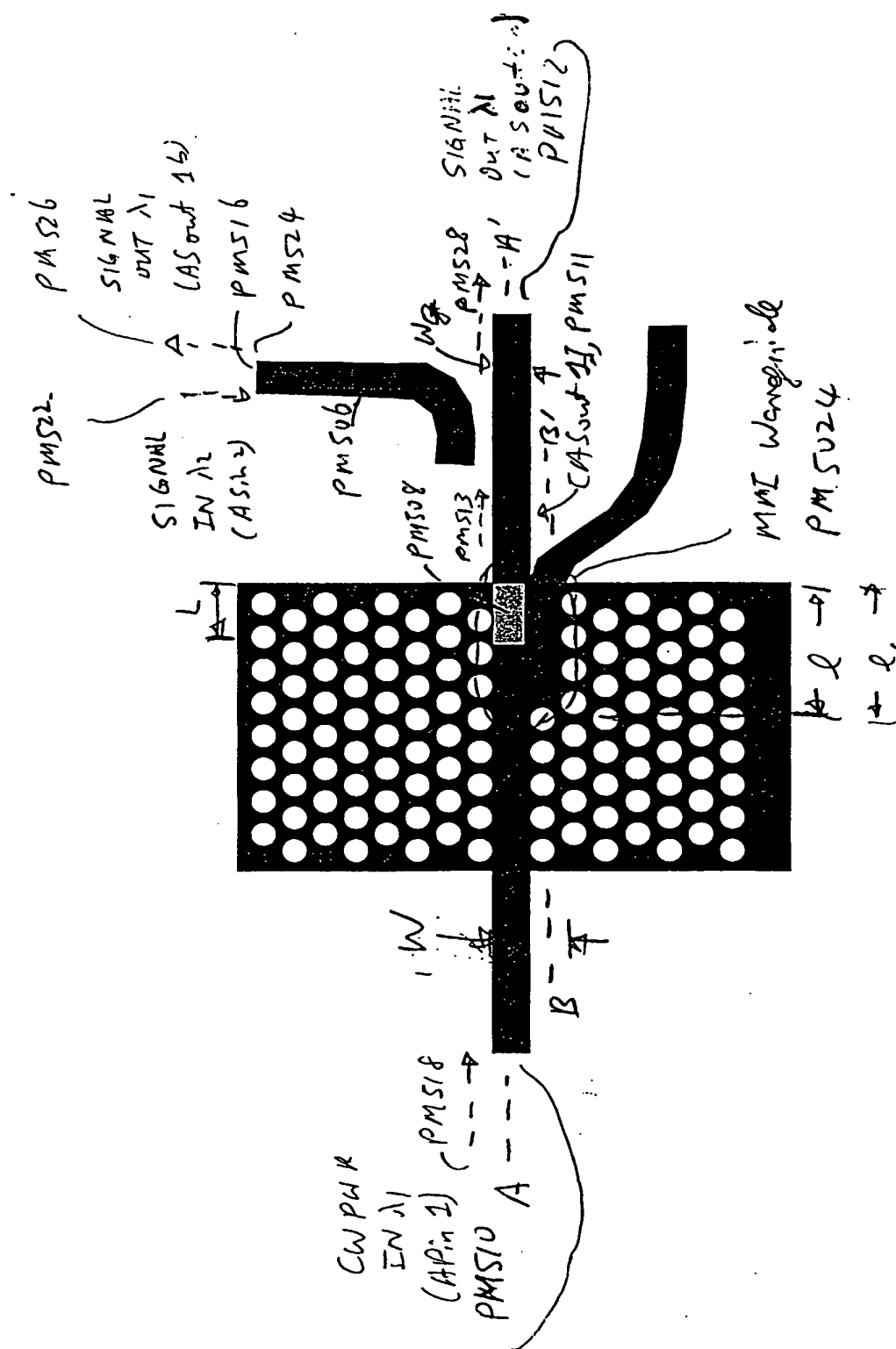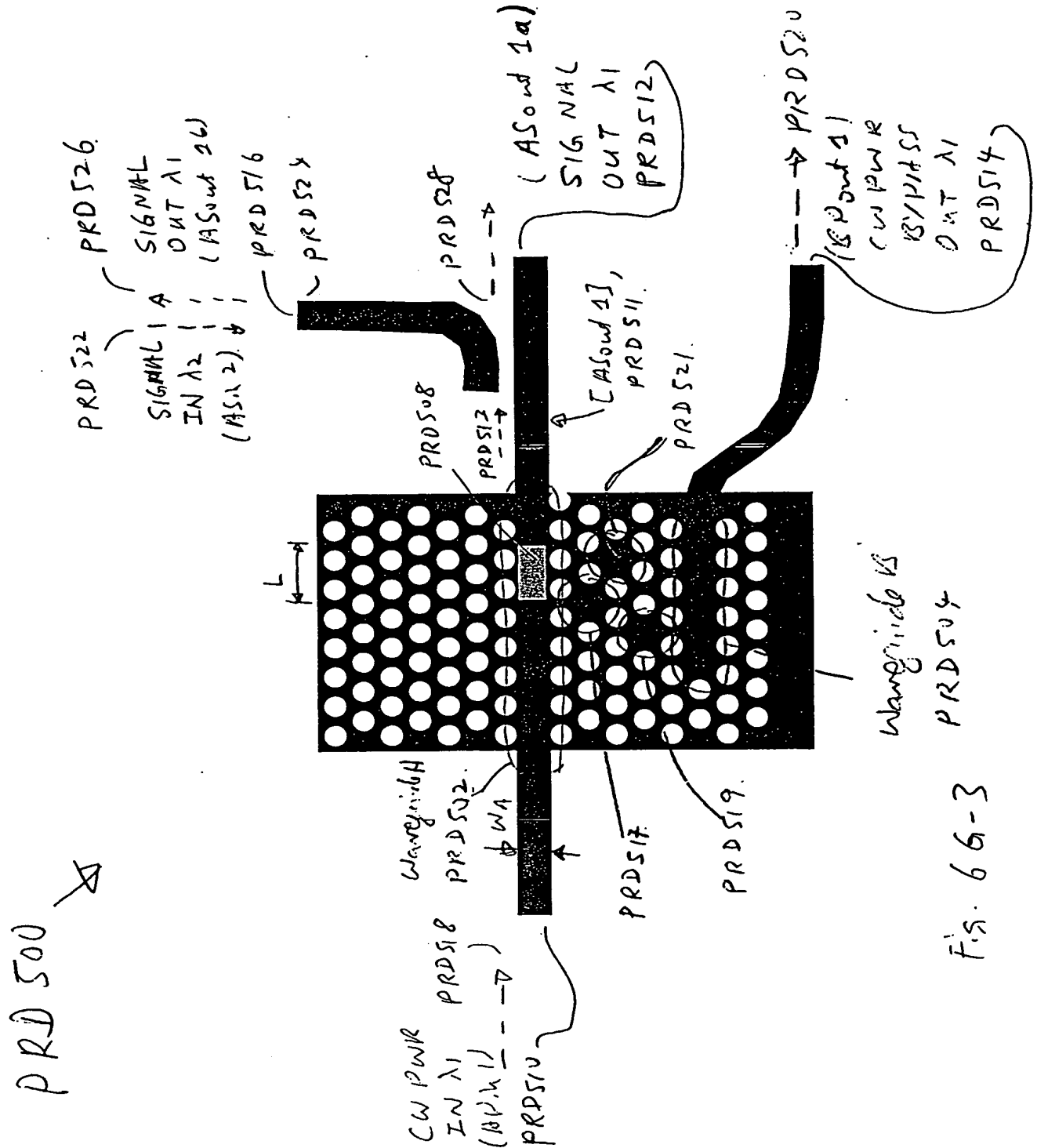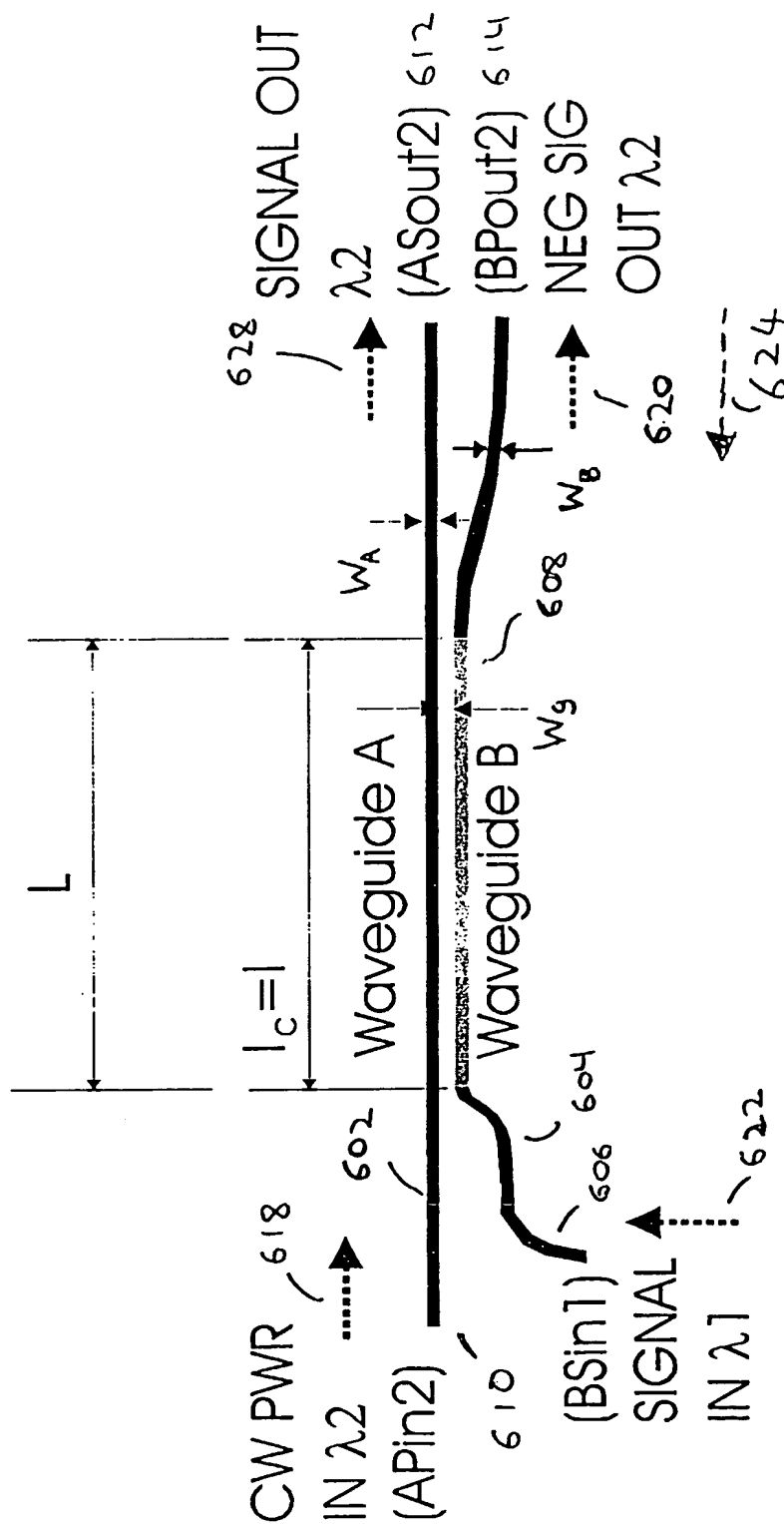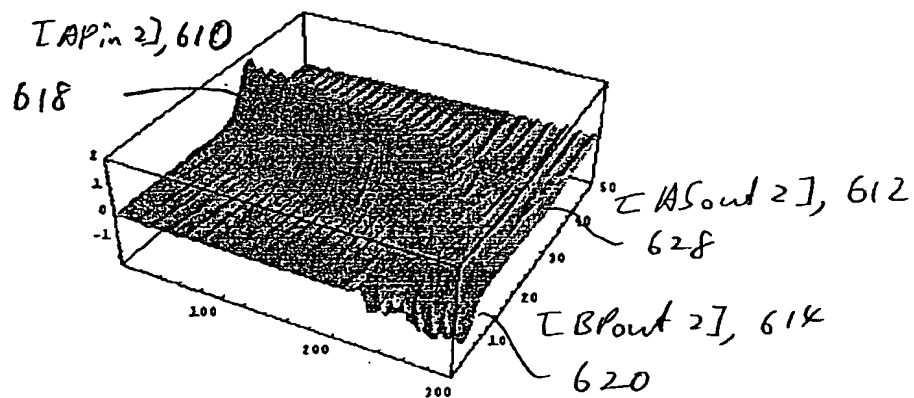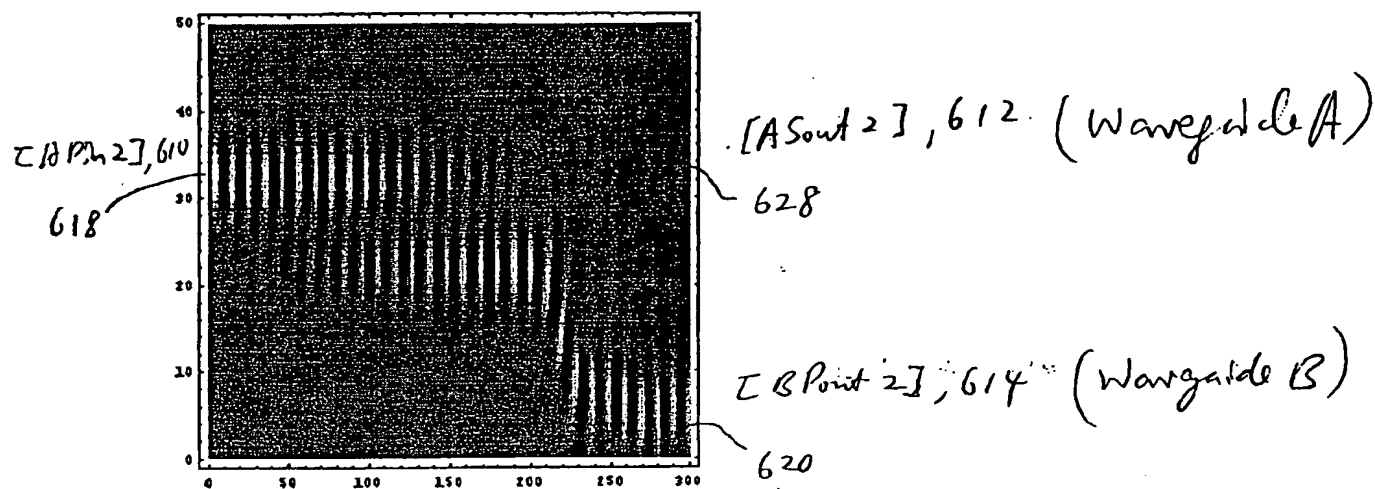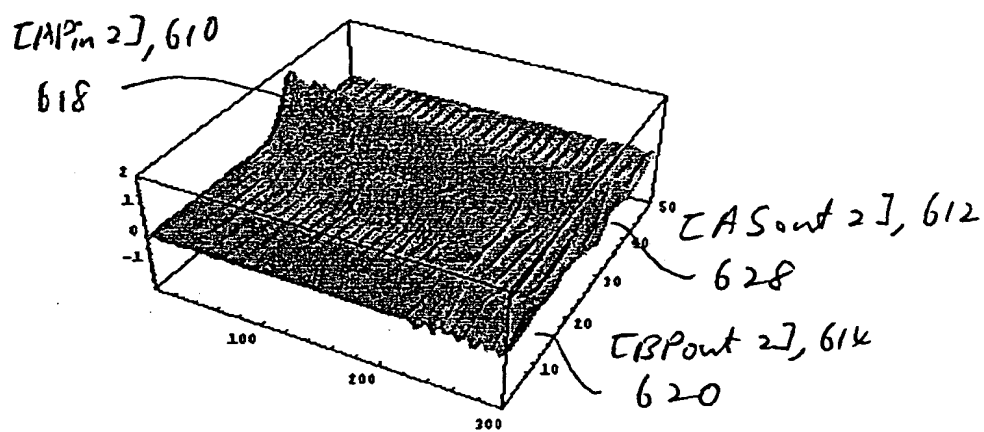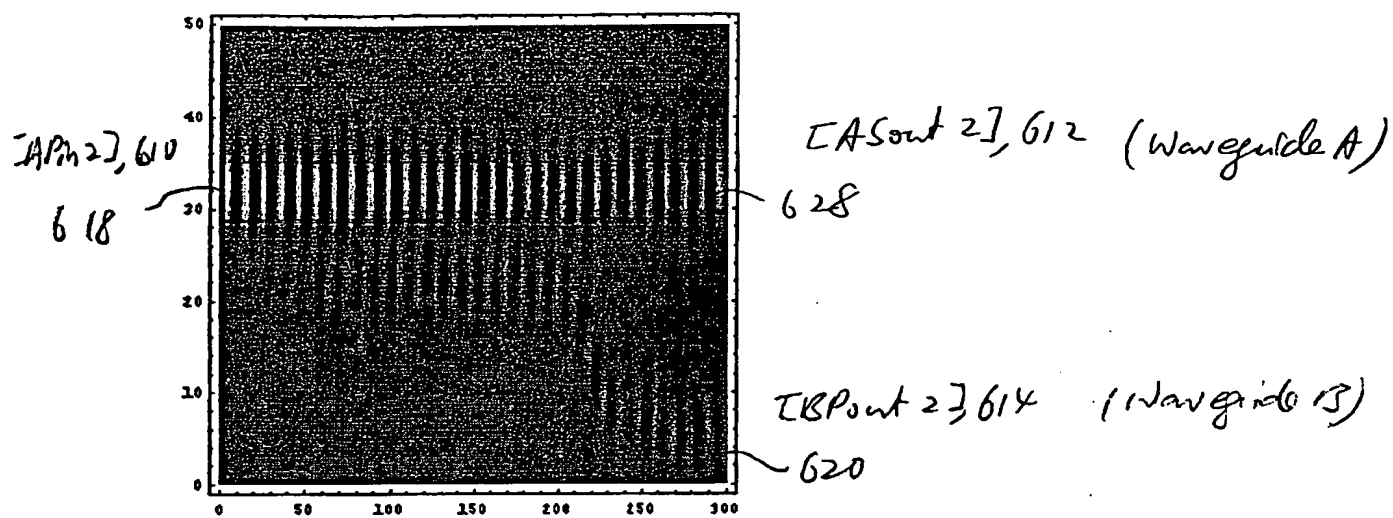
Fig - 7A-2

Fig 7A-3

FIG. 7AA

FIG. 7B

[Pin 2],
m 610

1 618

[AS out 2], M 612
M 628   ('Arm A).

[B Port 2], M 614
(Arm B)

M 620

[A Pin 2], M 610
M 618

[A S out 2], M 612
M.628

[B Port 2], M 614
M 620

Fig 7C-1

[P_in 2] M610
M618

[A Sout 2], M612
(Arm A)
M628

[BP out 2], M614
(Arm B)
M620

[BPin 2] M610
M618

[A Sout 2] M612
M628

[BP out 2], M614
M620
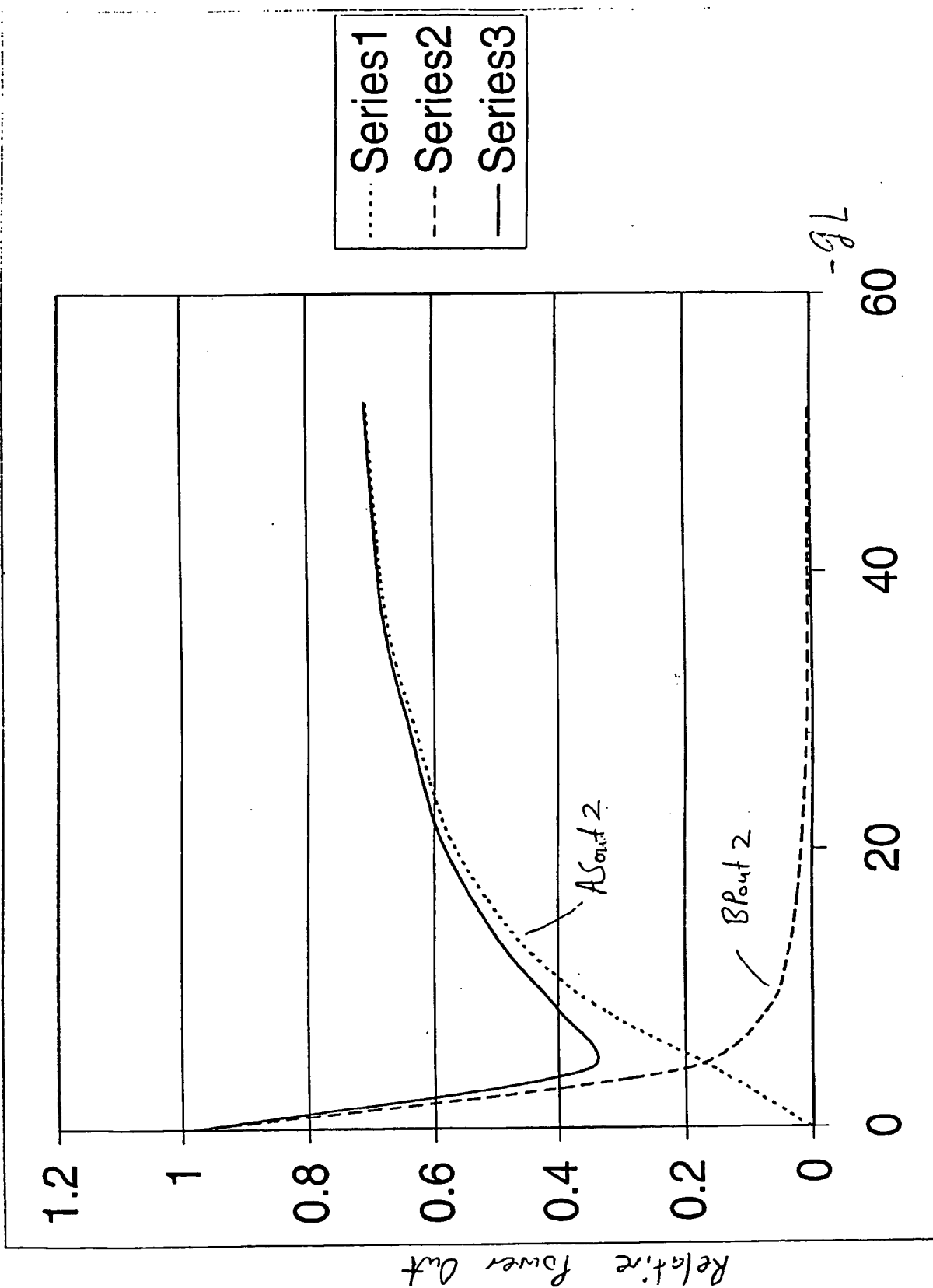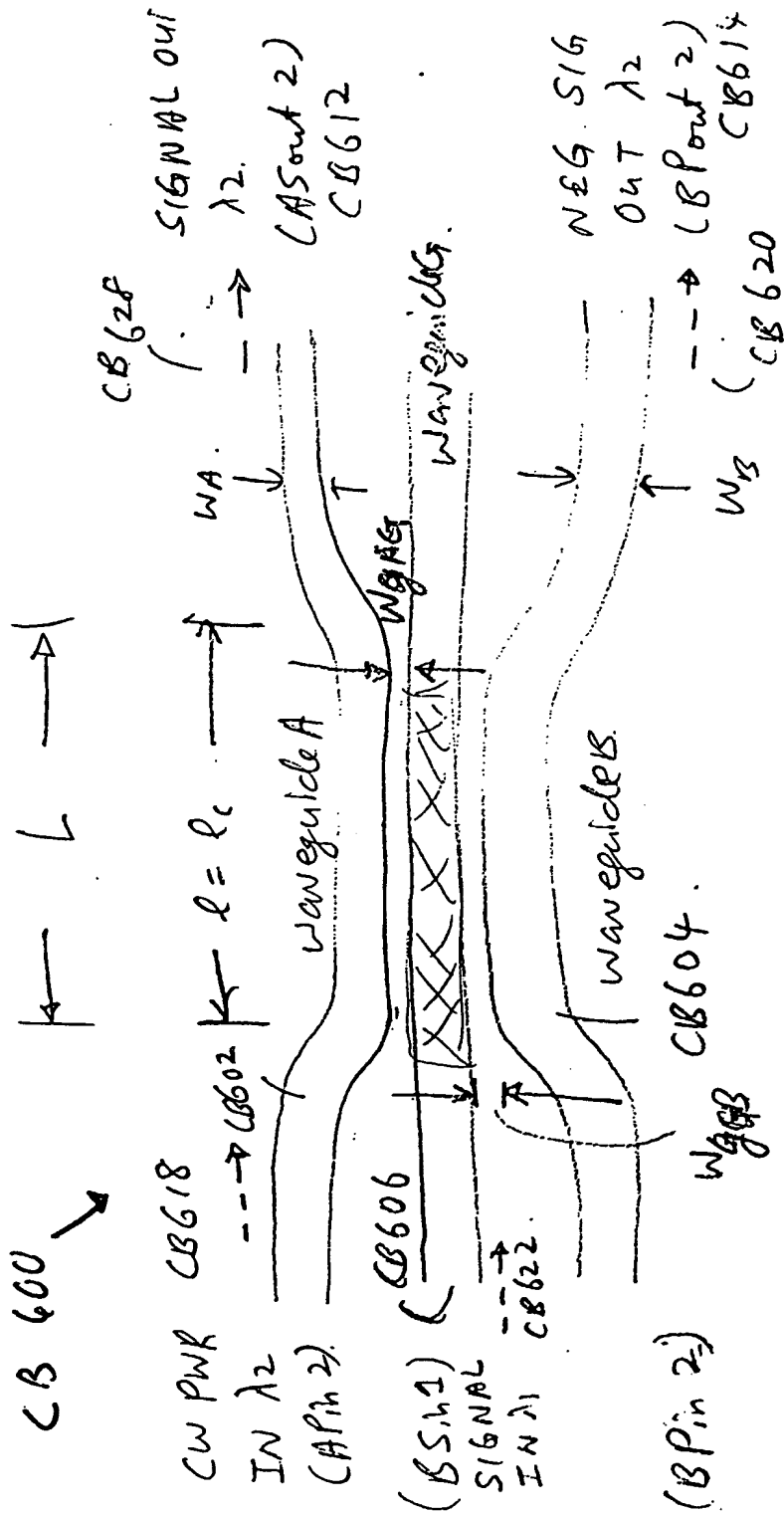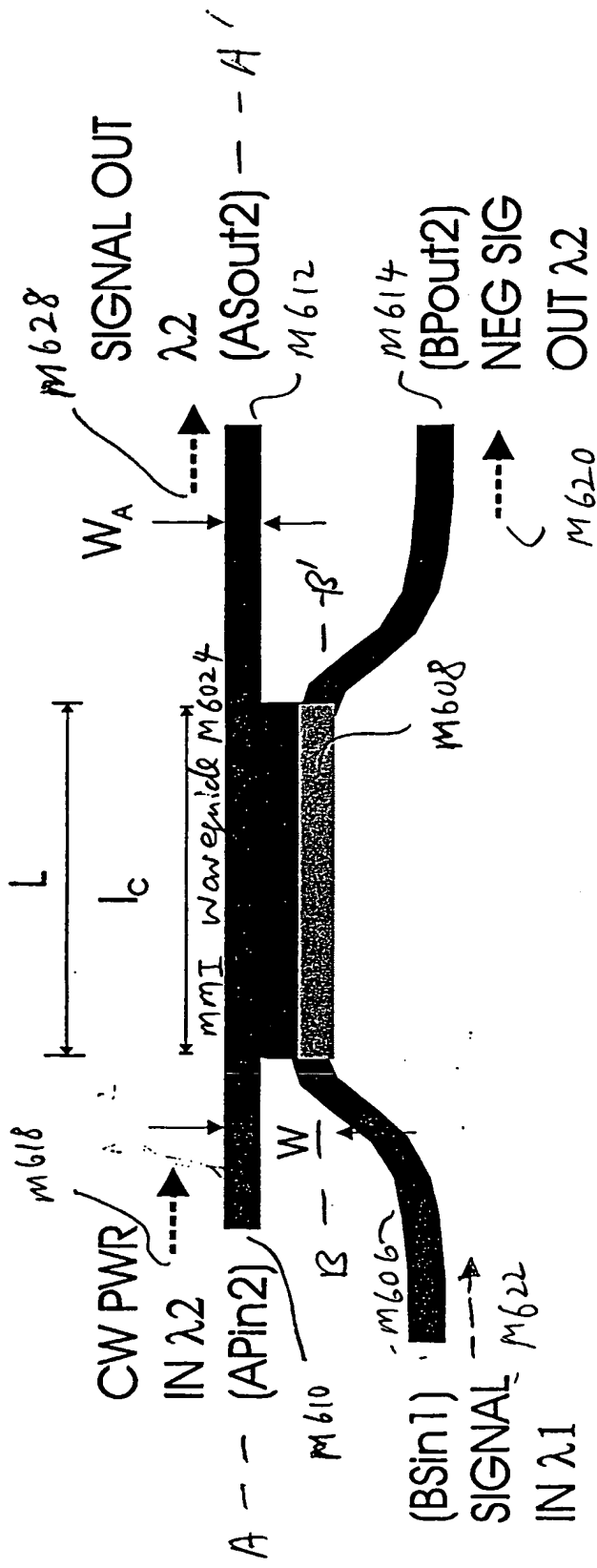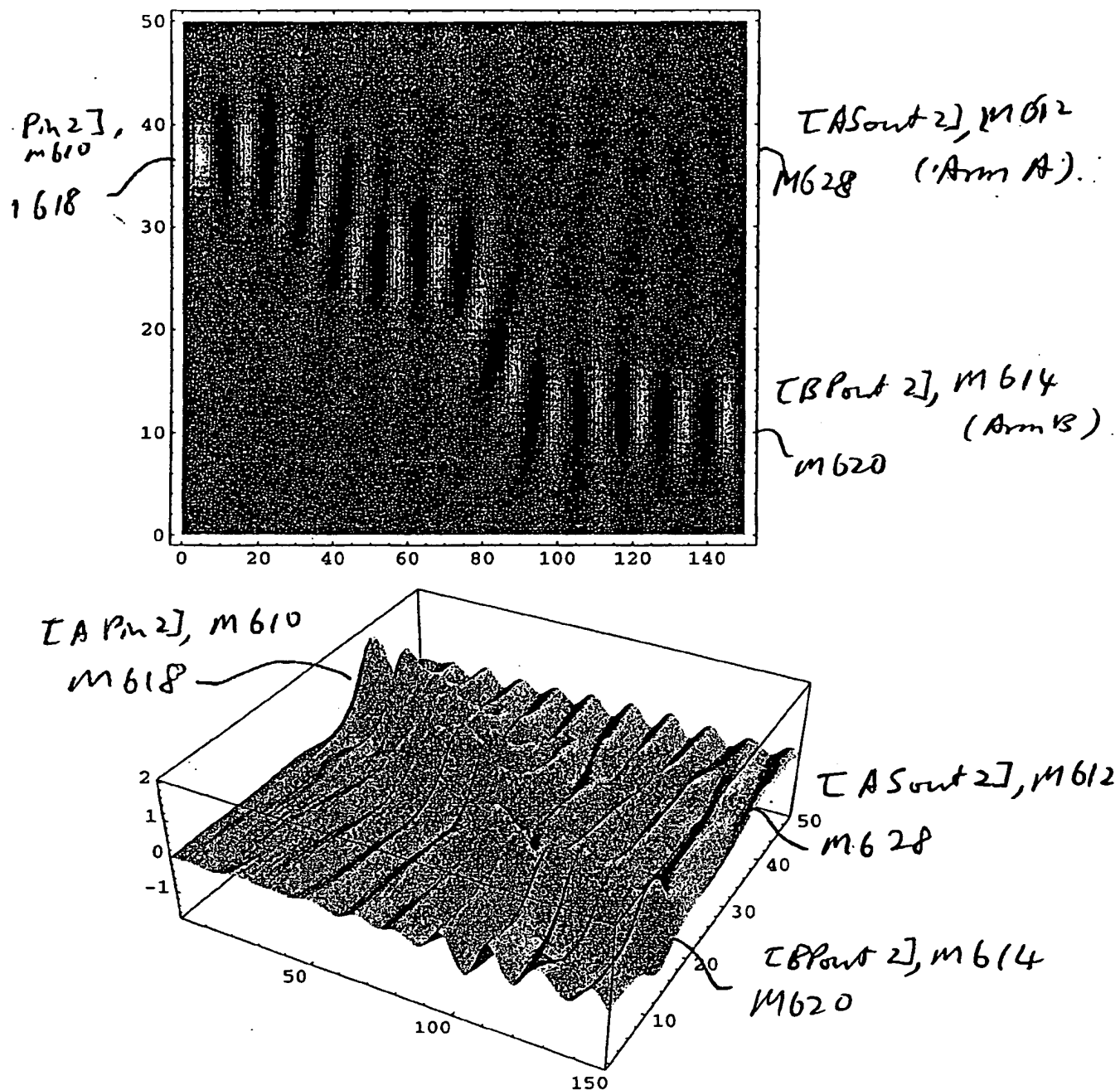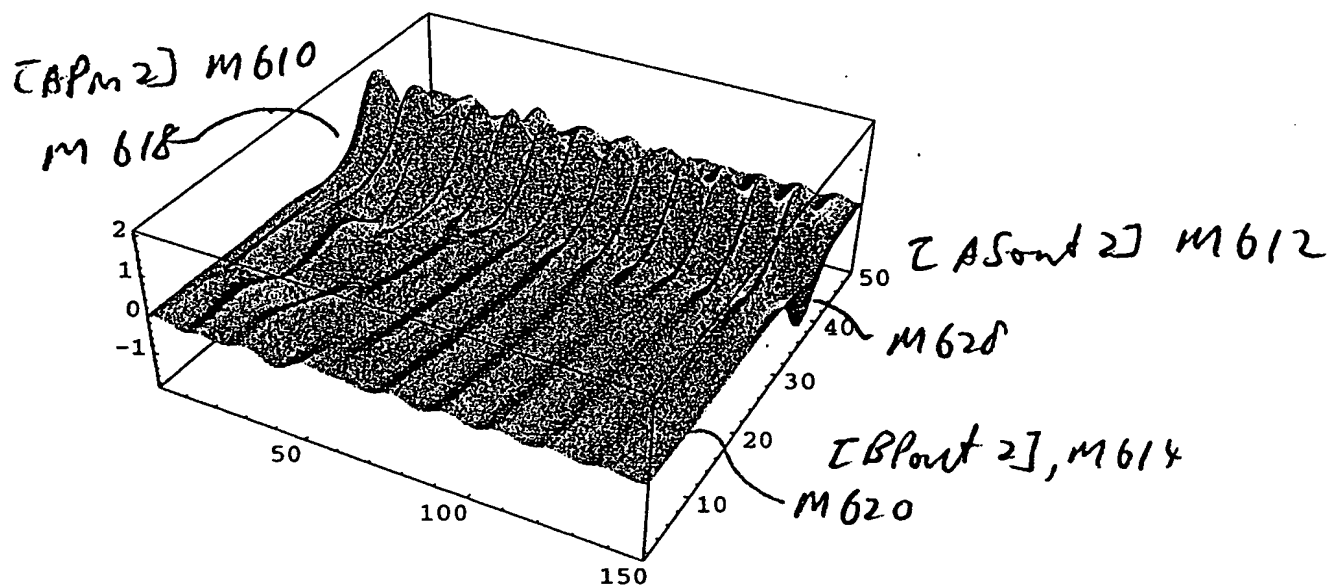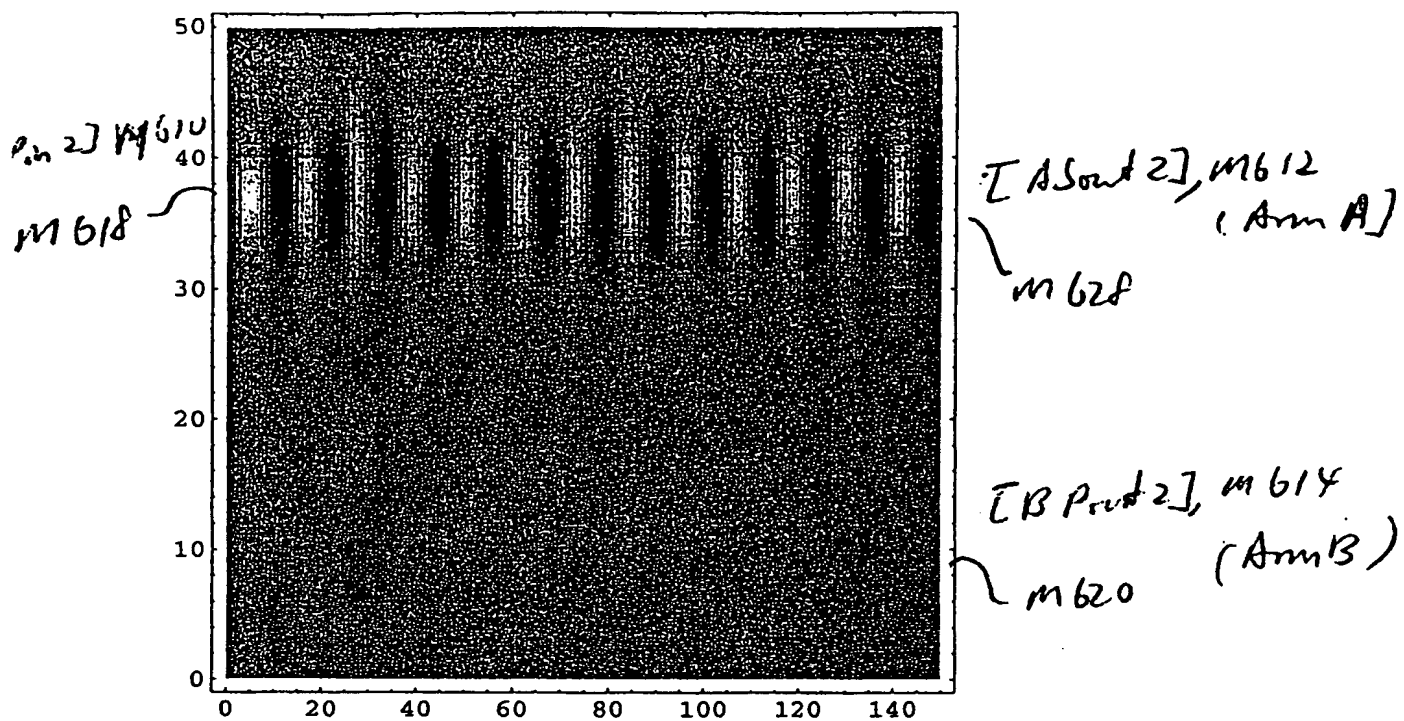
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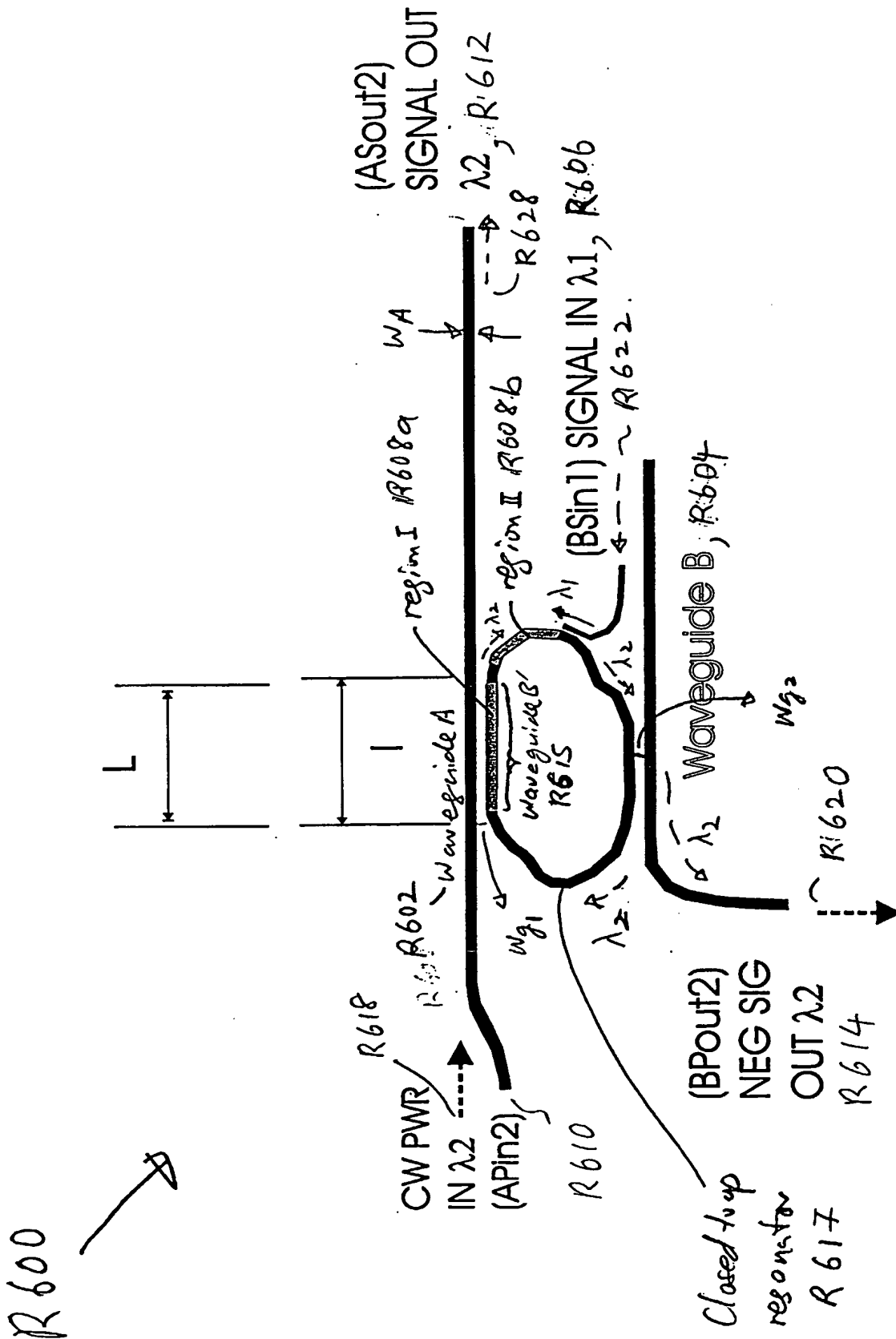
Fig. 7D-1

Fig. 7.D-2

Fig-7D-3
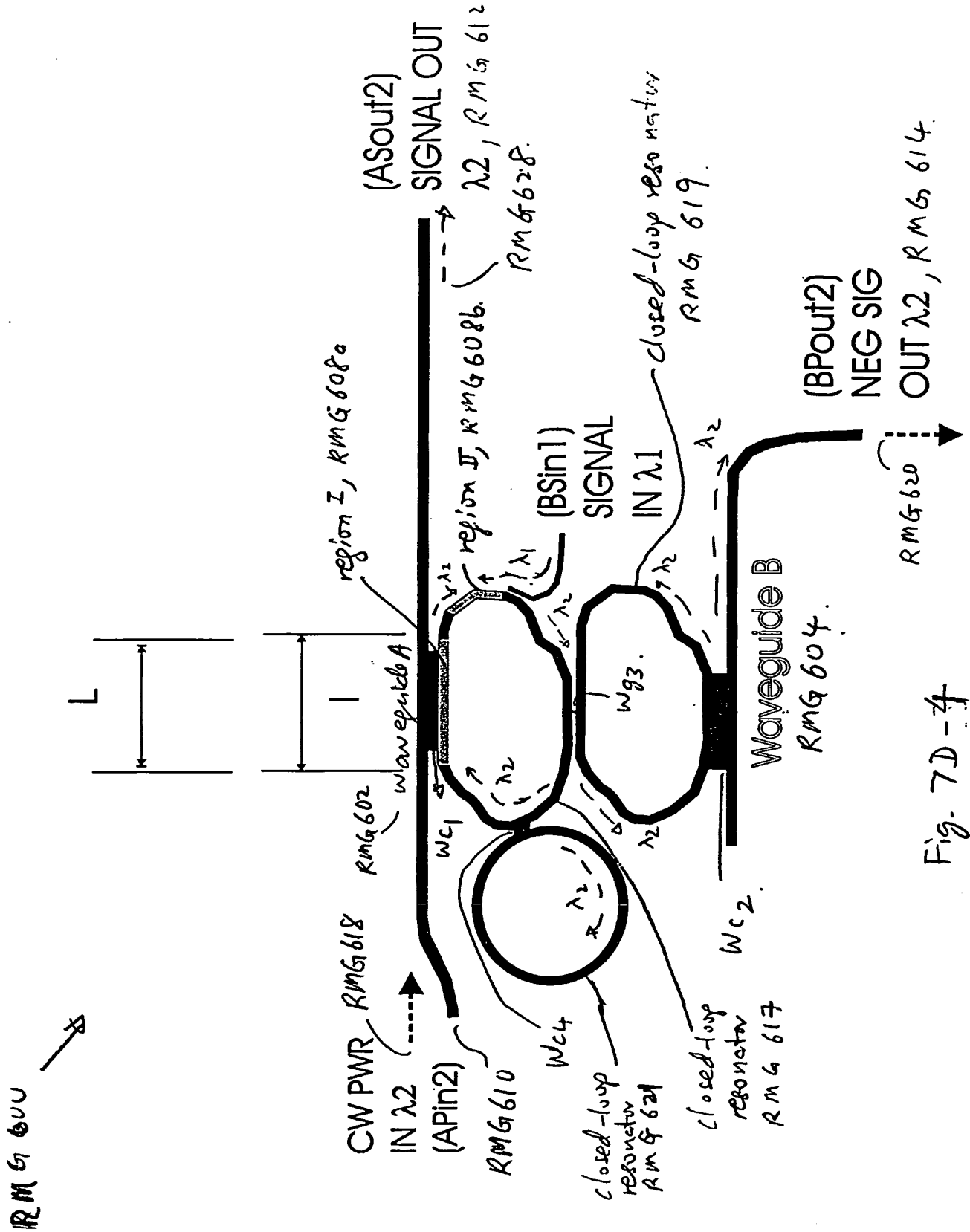
Fig. 7D-4
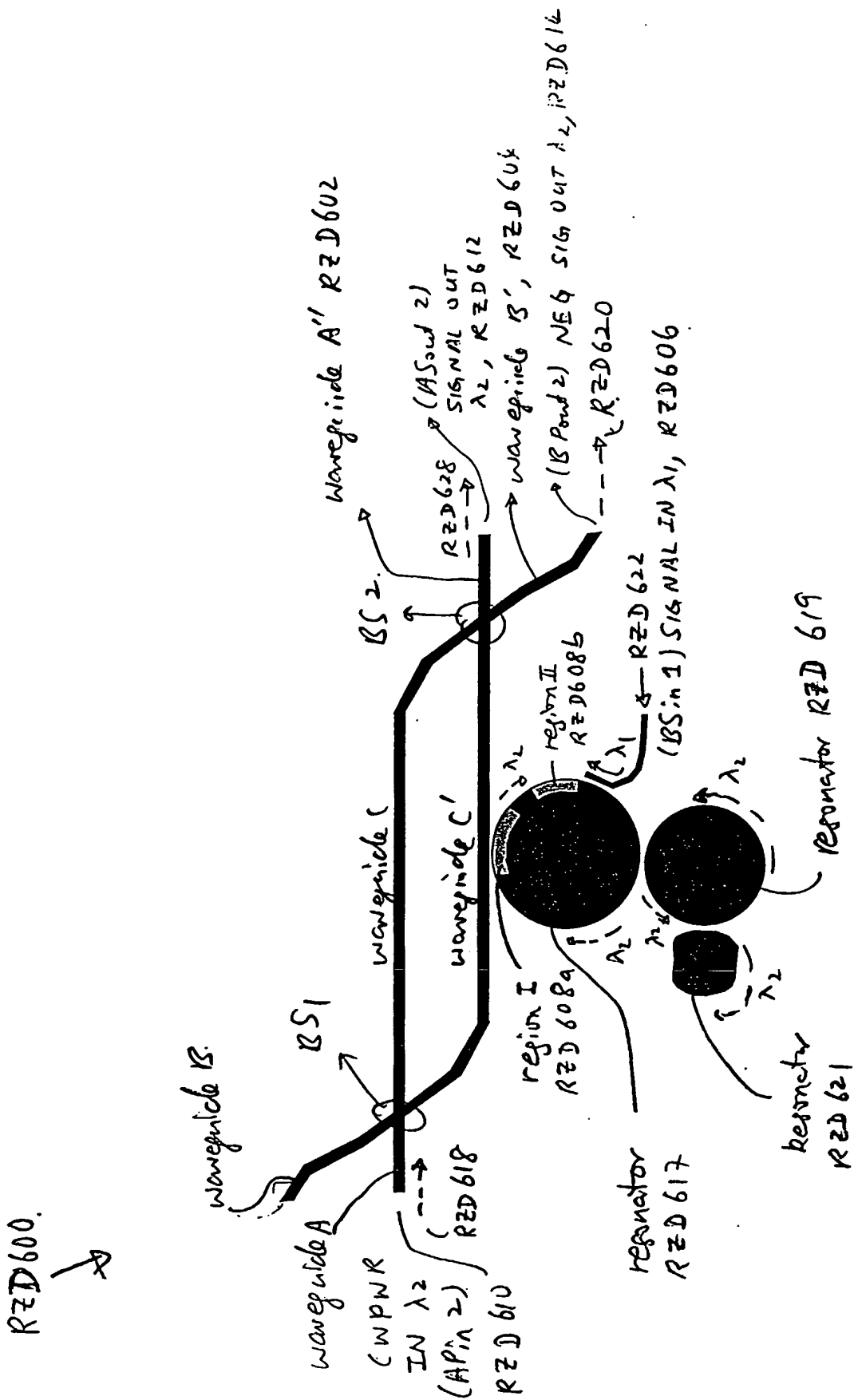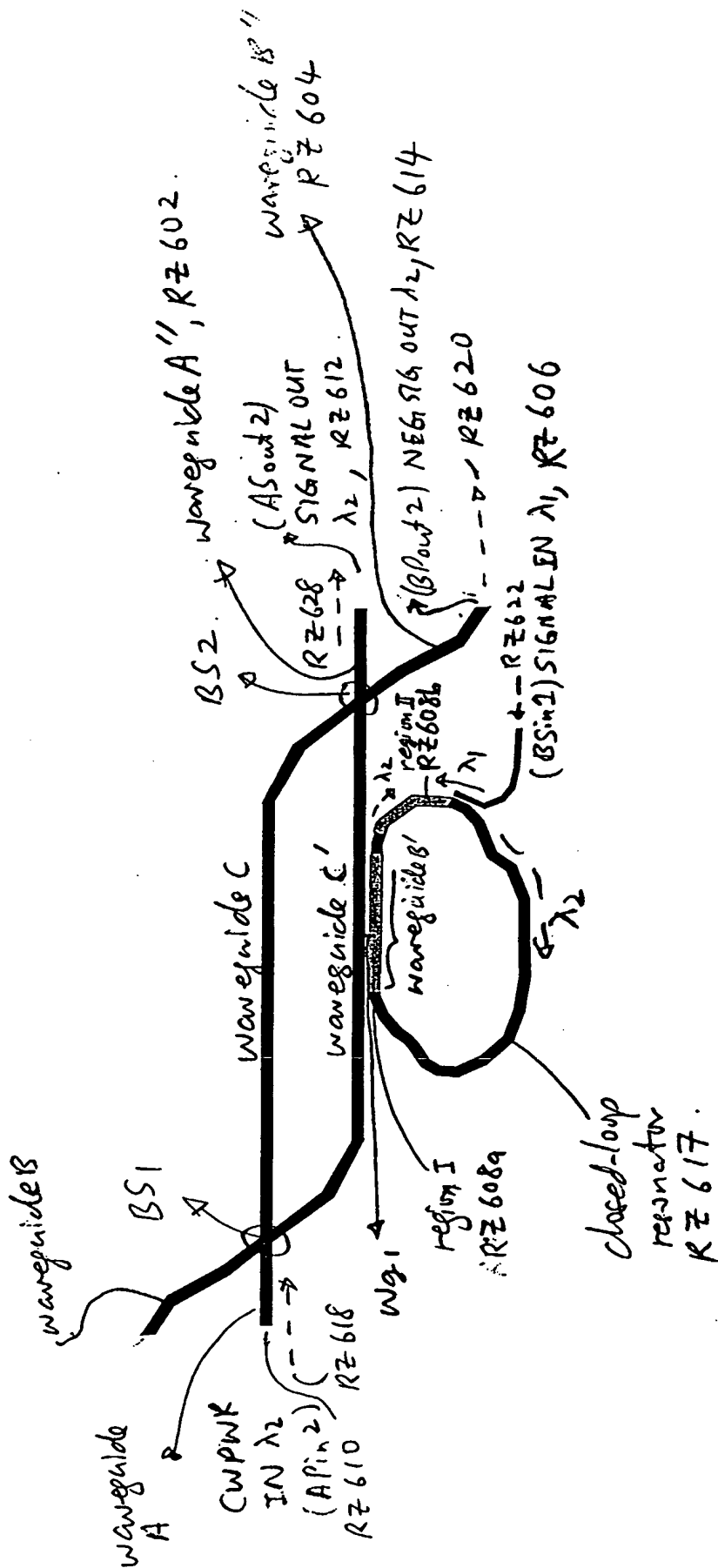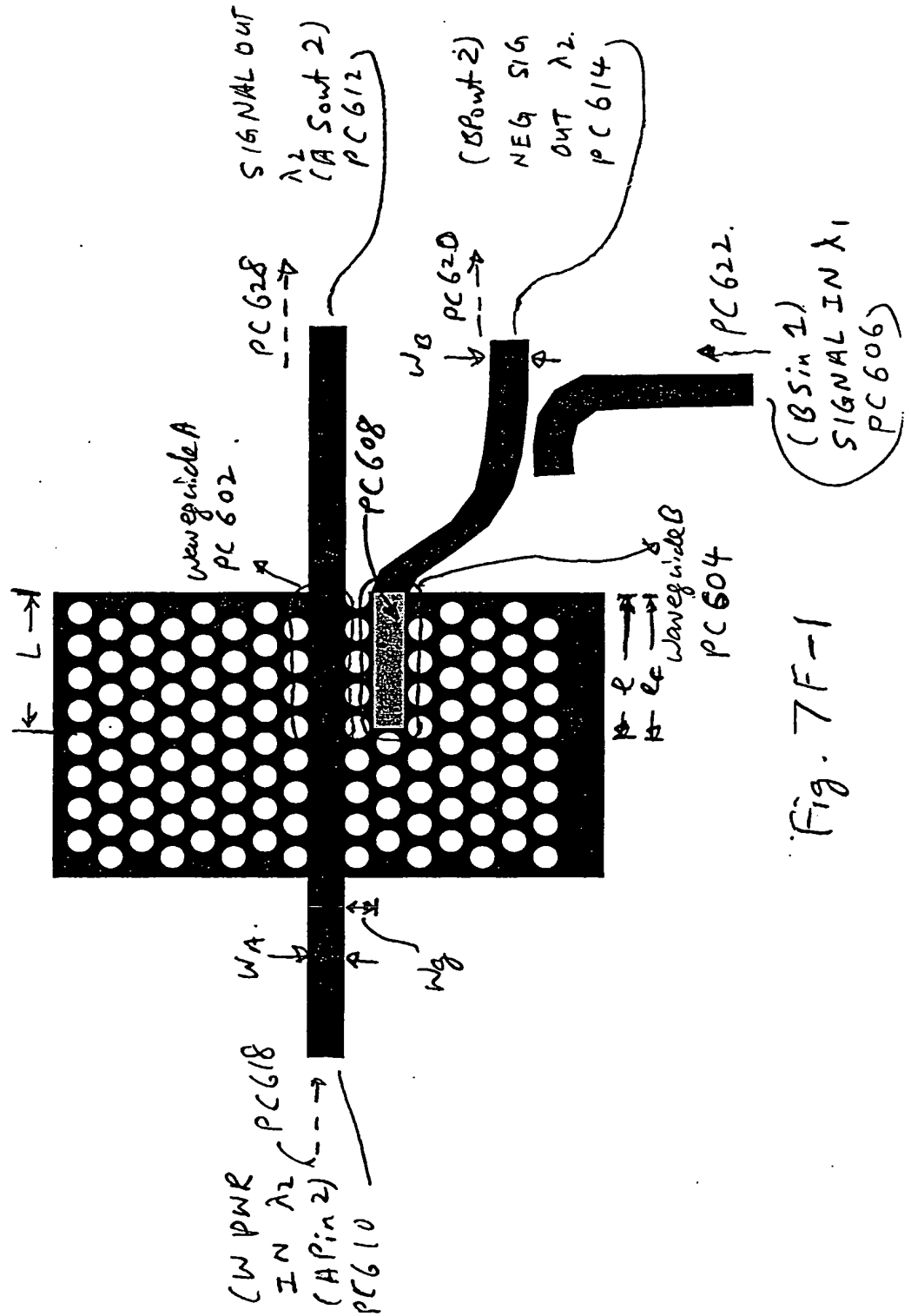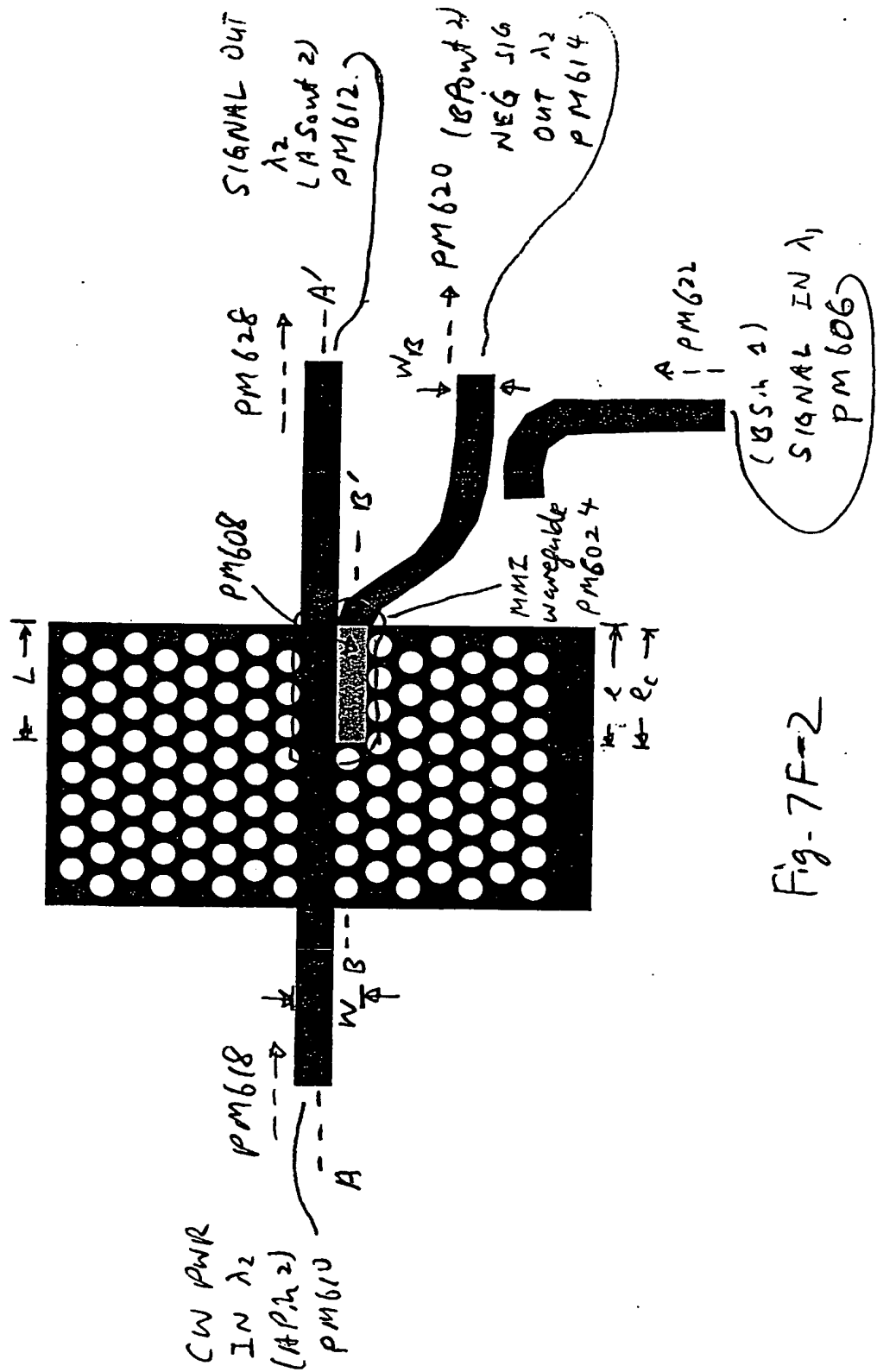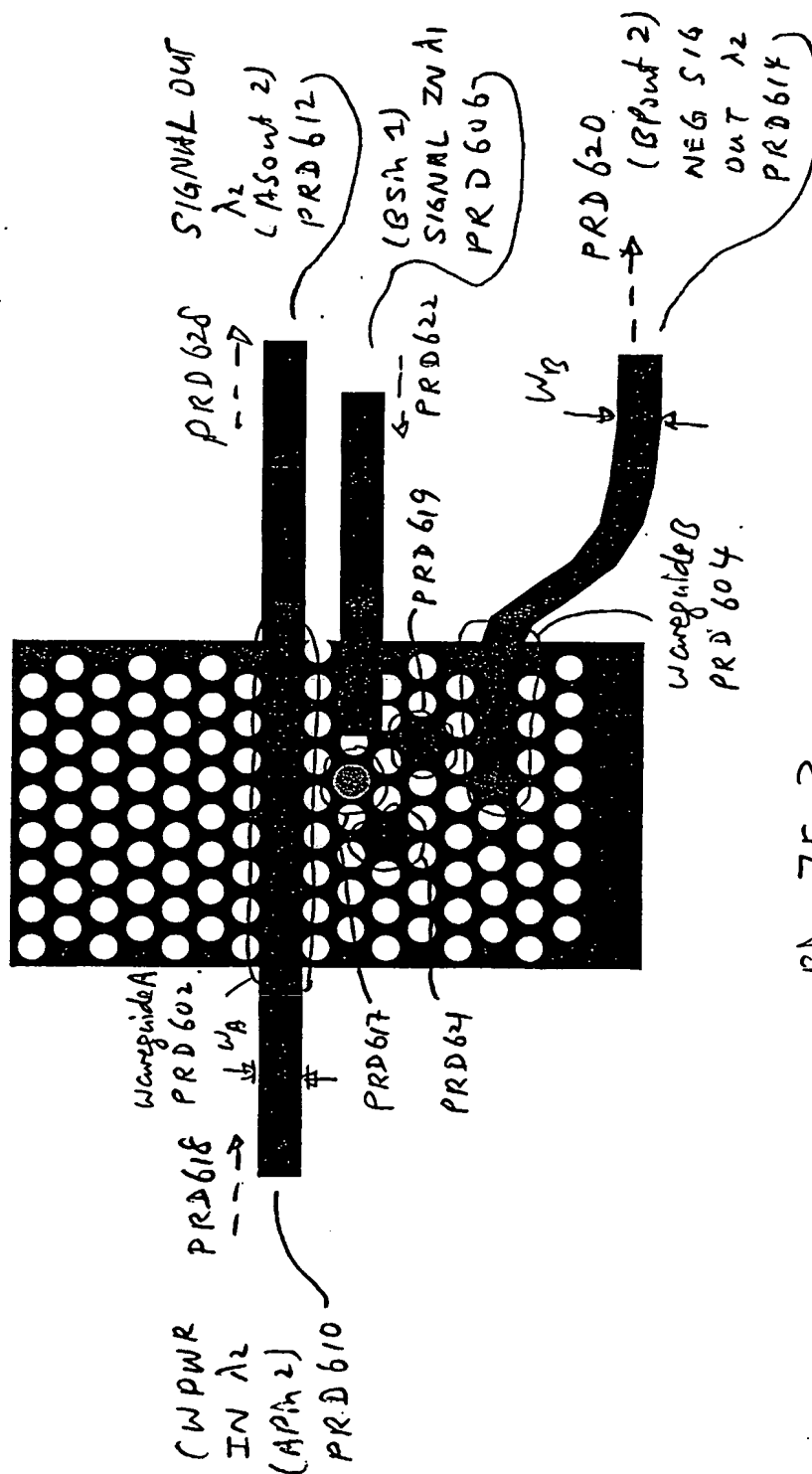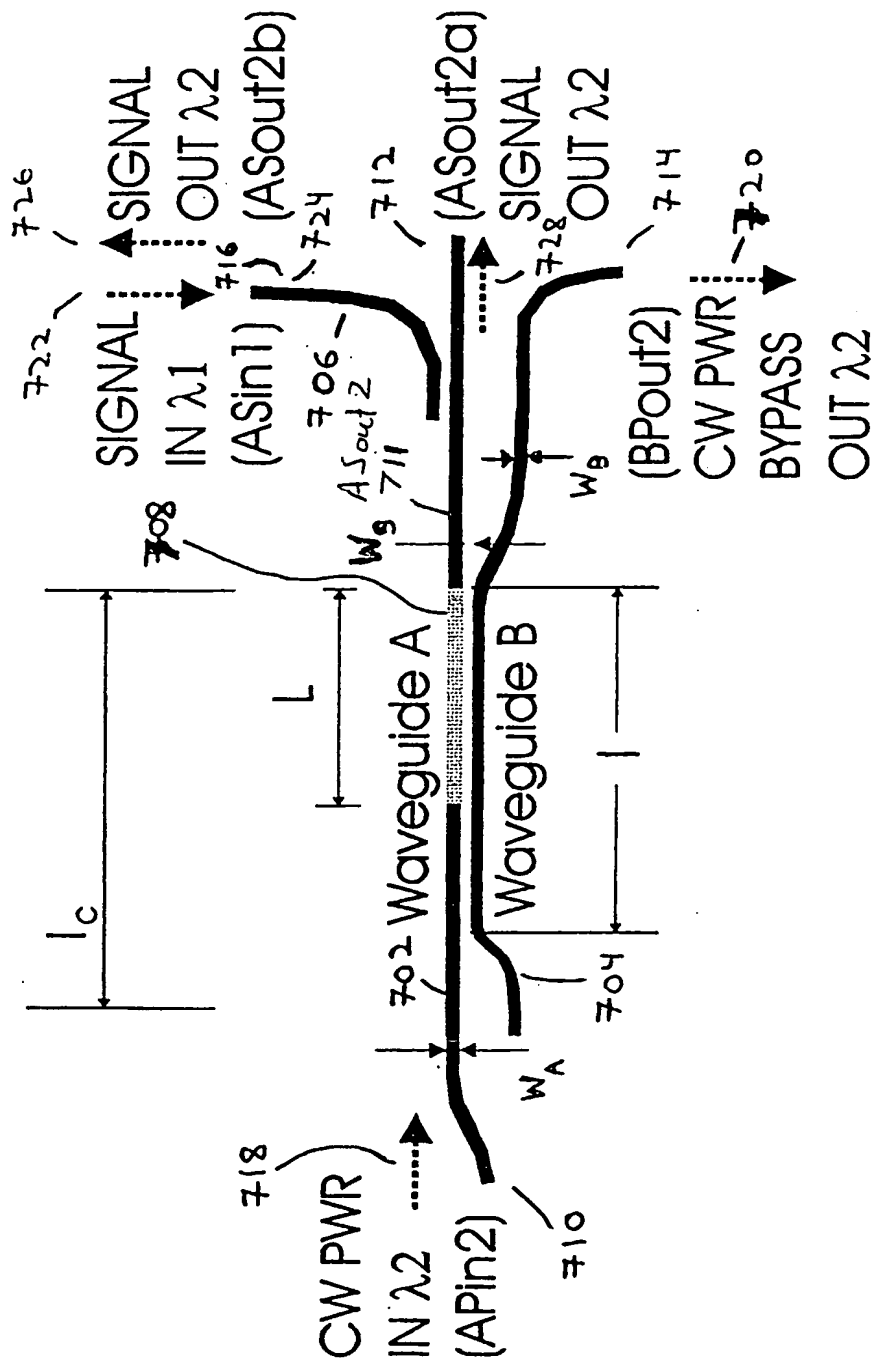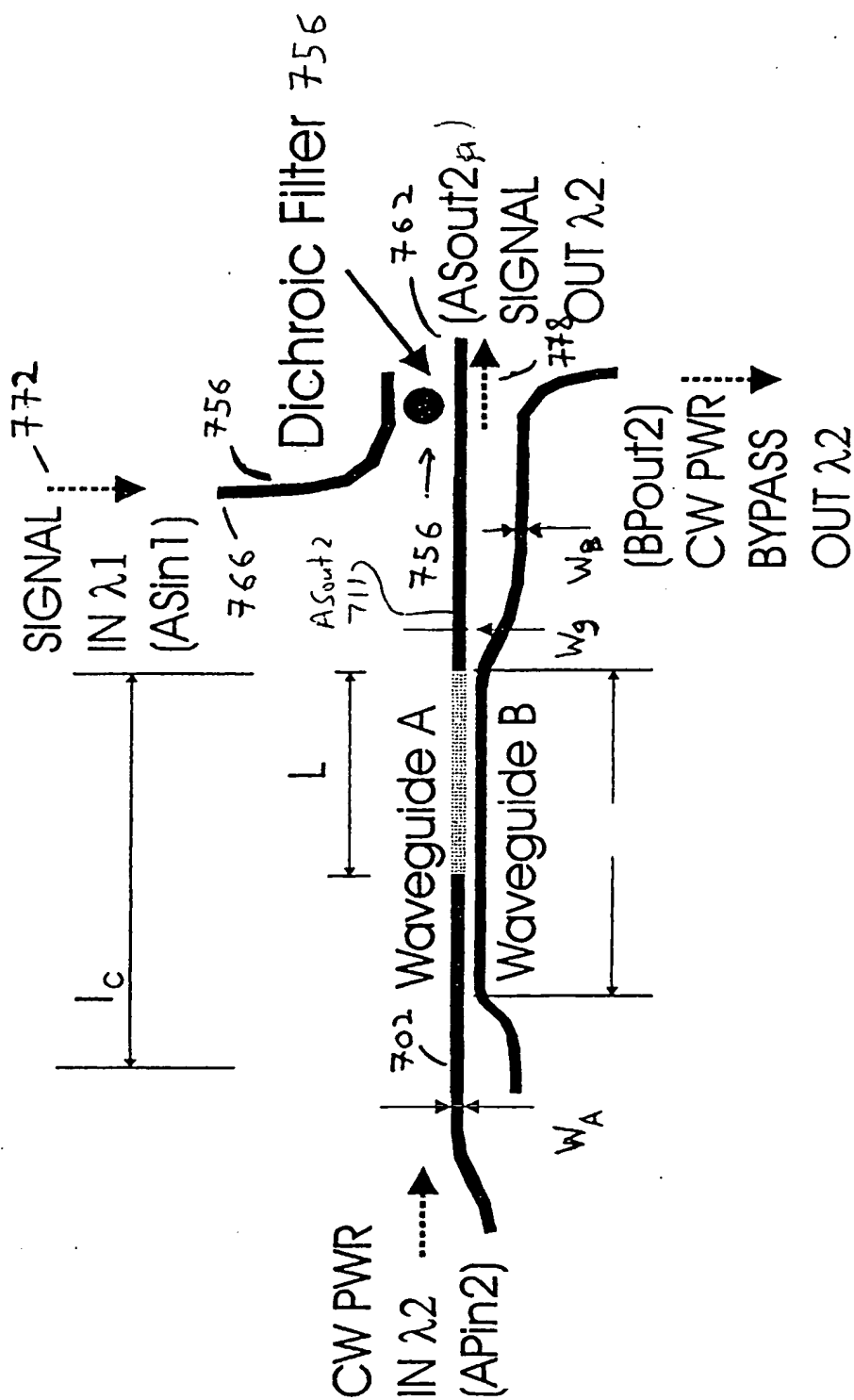
RMG 600

Fig. 7E-2

Fig. 7E-1

Fig. 7E-3.

Fig. 7F-1

Fig-7F-2

Fig. 7F-3.

FIG. 8A

FIG. 8B

FIG. 9

(Waveguide A) A Pin 1 →

(Waveguide B)

→ A Out 1

→ B Pout 1

A Pin 1 →

A Sout 1

B Pout 1

FIG   9A - 1

Waveguide A)
APin 1 →

(Waveguide B)

→ ASout 1

→ BPout 1

APin 1

ASout 1

BPout 1

FIG 9A-2

FIG. 9A-3

FIG. 10

FIG. 11

FIG. 12

FIG. 13

1518
A1
1510

1518
A2 1512   (Waveguide A)

B2 1514   (Waveguide B)

520

1518
A-1
1510

1518
A2 1512

B2 1514

520

Fig. 13A

A5 1510
1518

A2 1512
(Waveguide A)
1518

B2 1514
(Waveguide B)
1520

A1 1510

1518

1518

A2 1512

B2 1514

520

Fig. 13 B

1518

1518

A2 1512'   (Waveguide A)

H 1510

B2 1514   (Waveguide B)

1520

1518

A1 1510'

1516

A2 1512

B2 1514

1520

Fig. 13 C

FIG. 13D

FIG. 14

A1 1610
618

A2 1612 (Waveguide A)
1618

B2 1614 (Waveguide B)
1620

A1 1610
1618

A2 1612
1618

B2 -1614
1620

FIG 14A

A1 1612
1618

A2 1612   (Waveguide A)
16 AB

B.2 .1614   (Waveguide B)
1620

A1... 1610
1618

A2   1612
16 AB

B.2   1614
1620
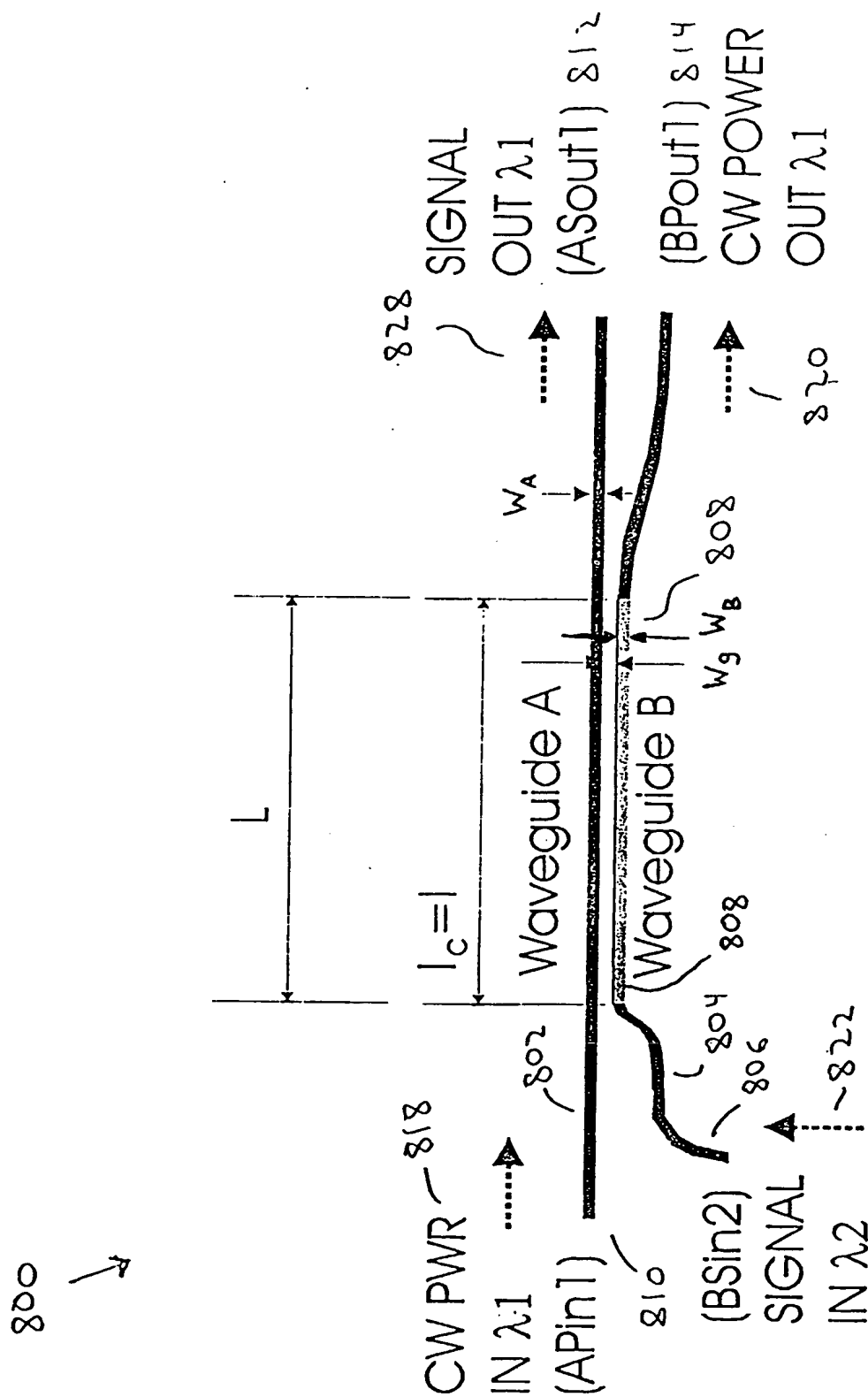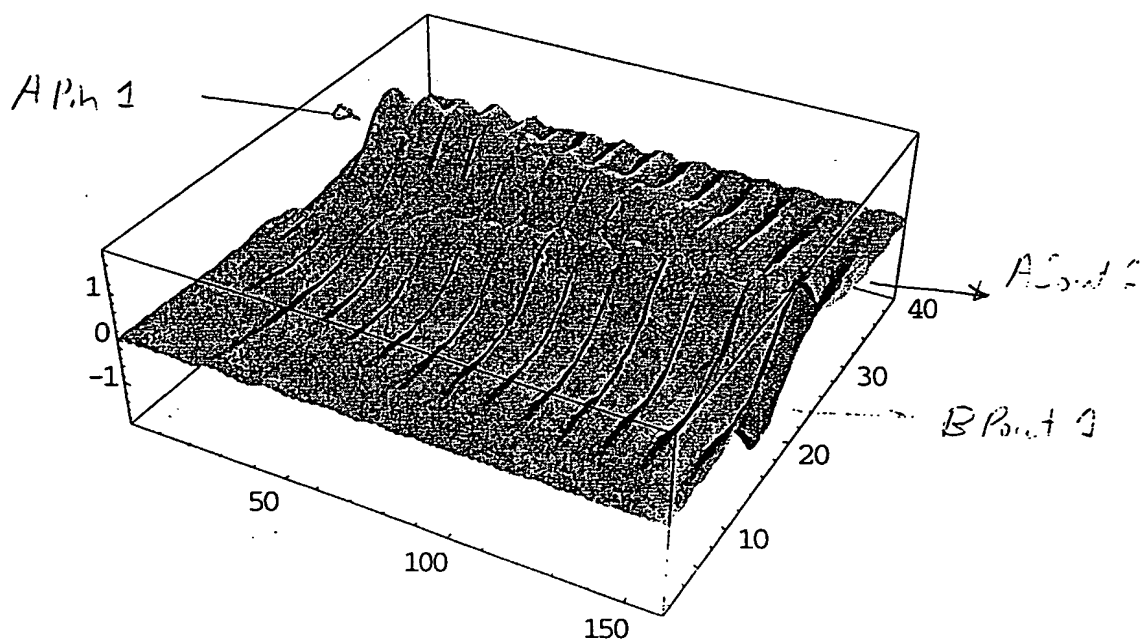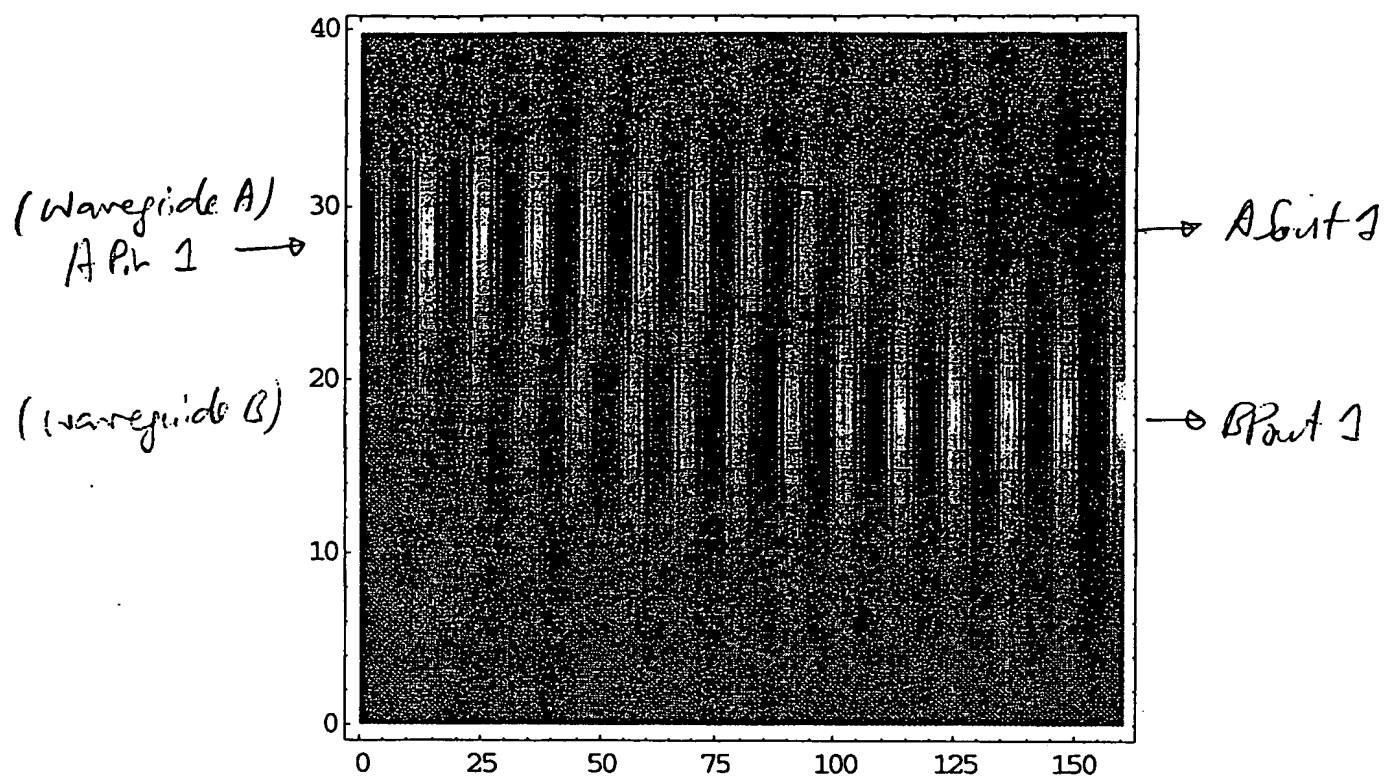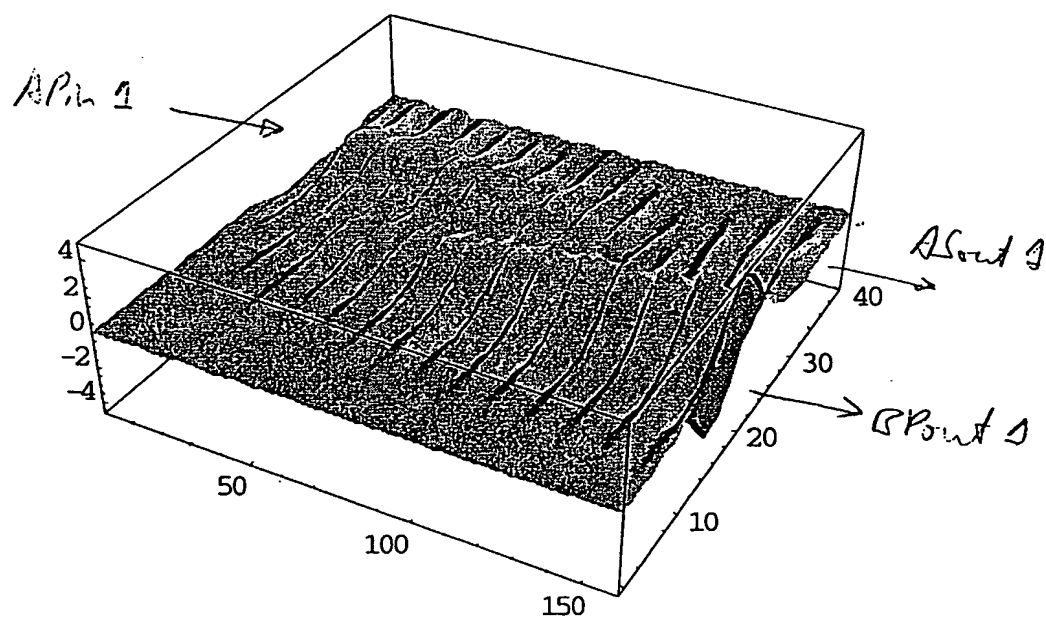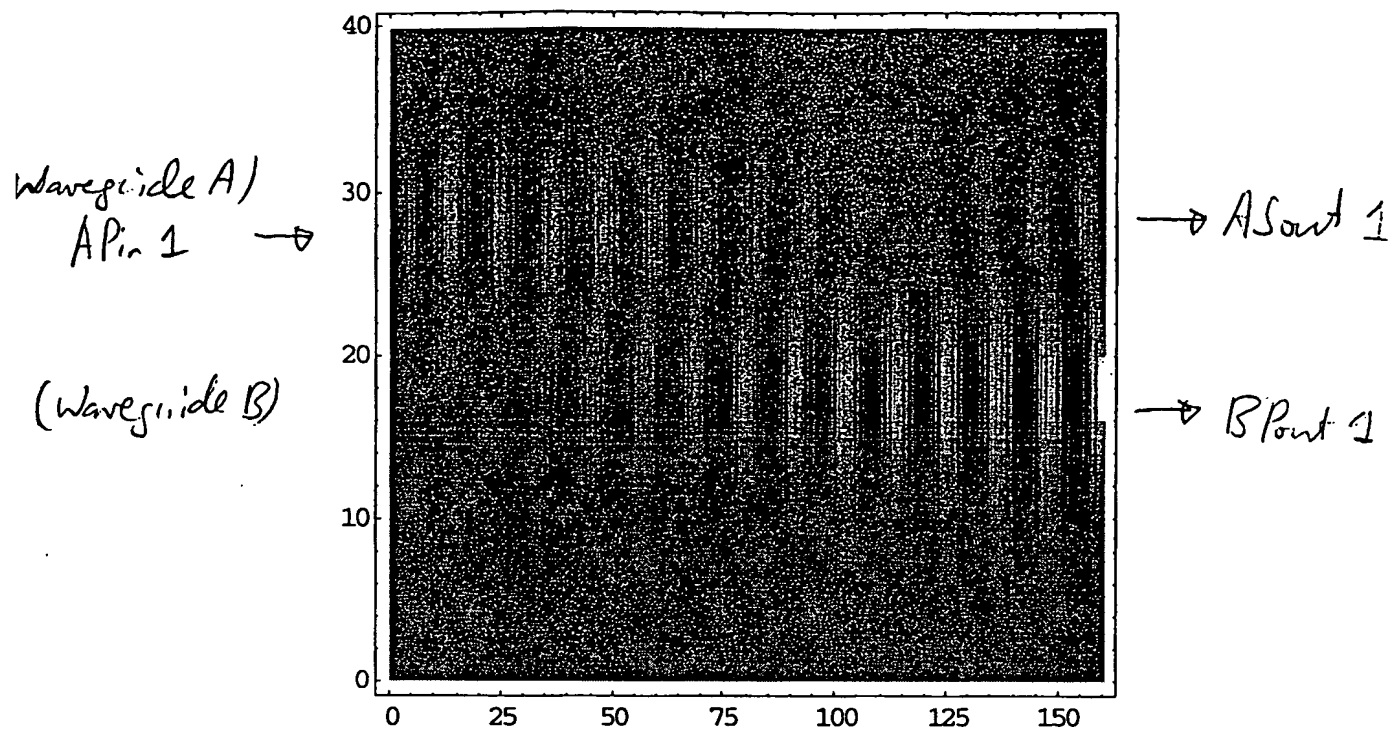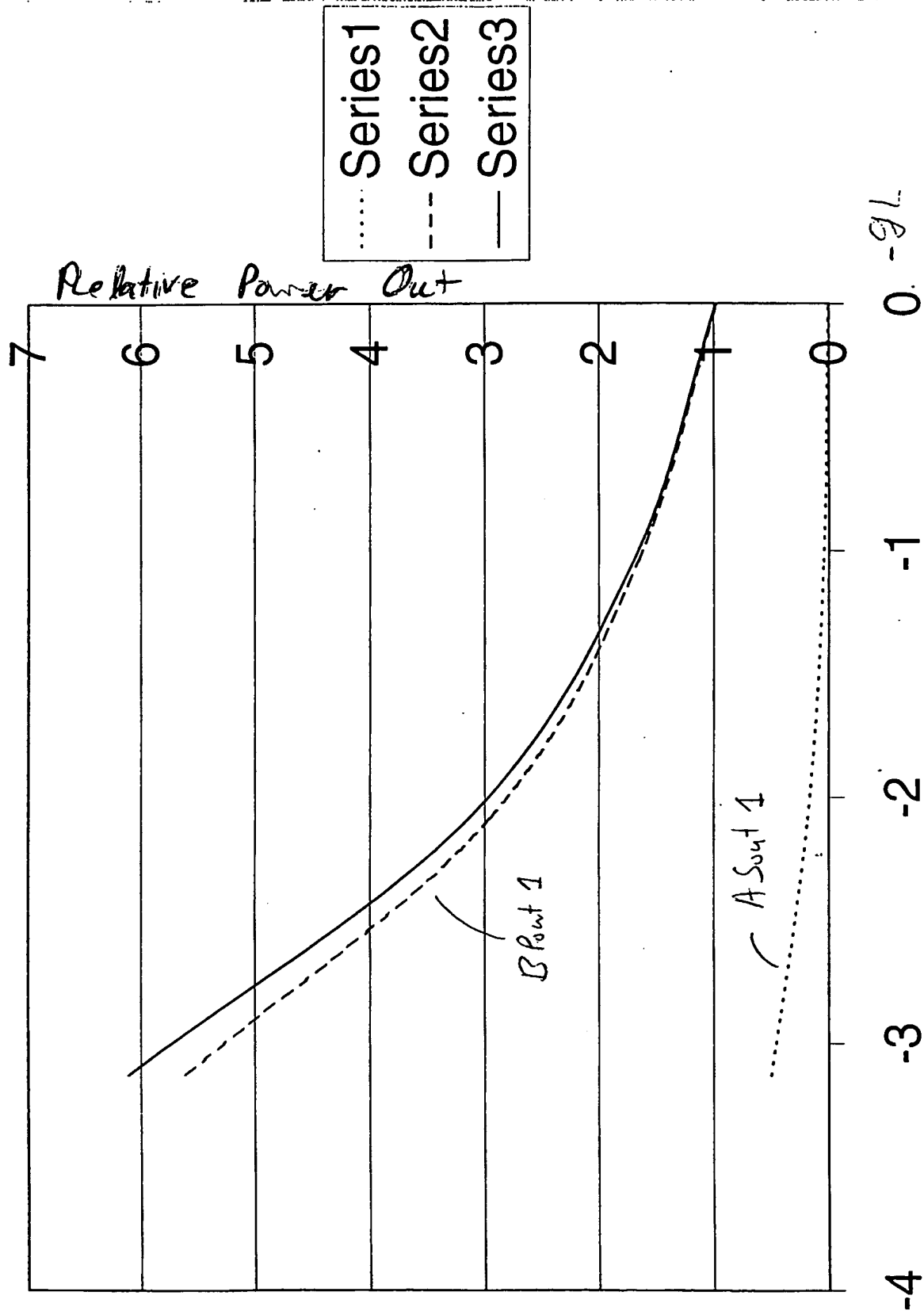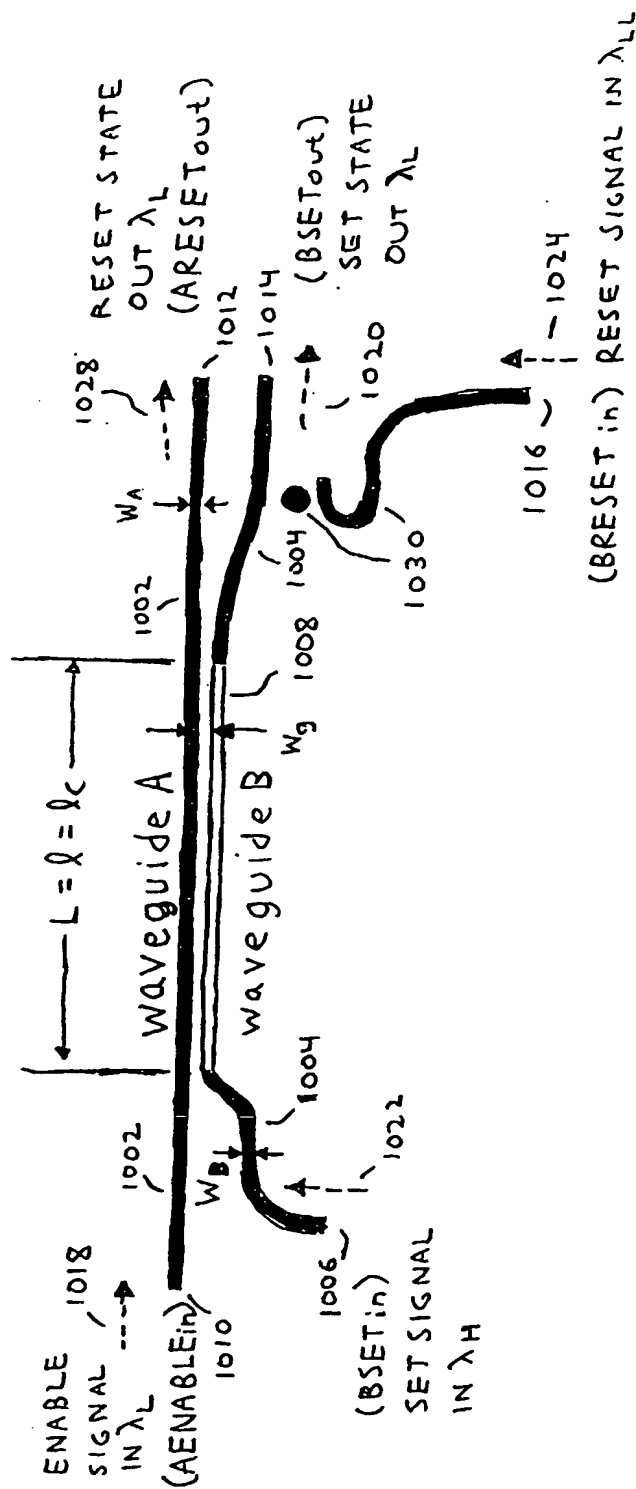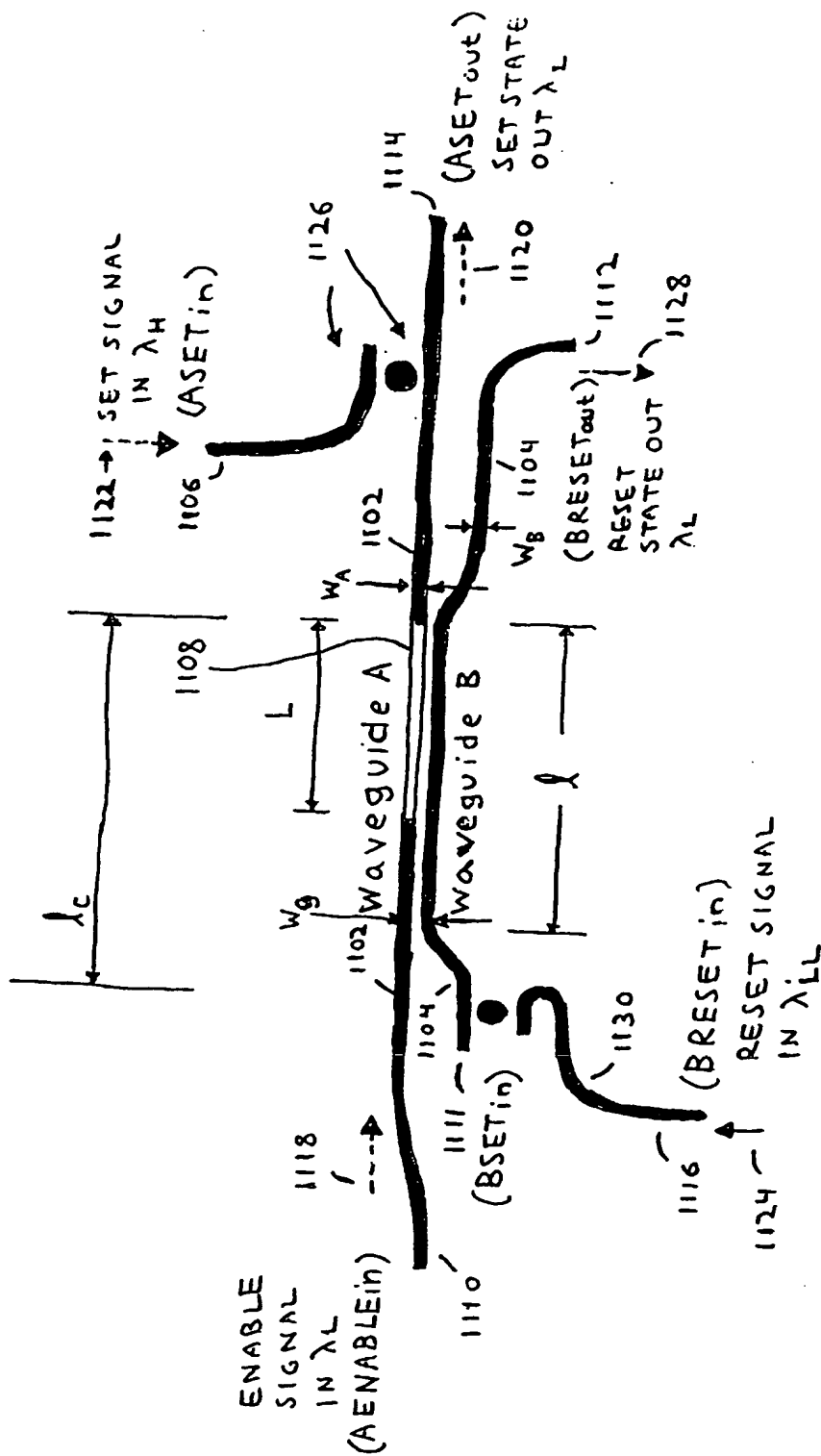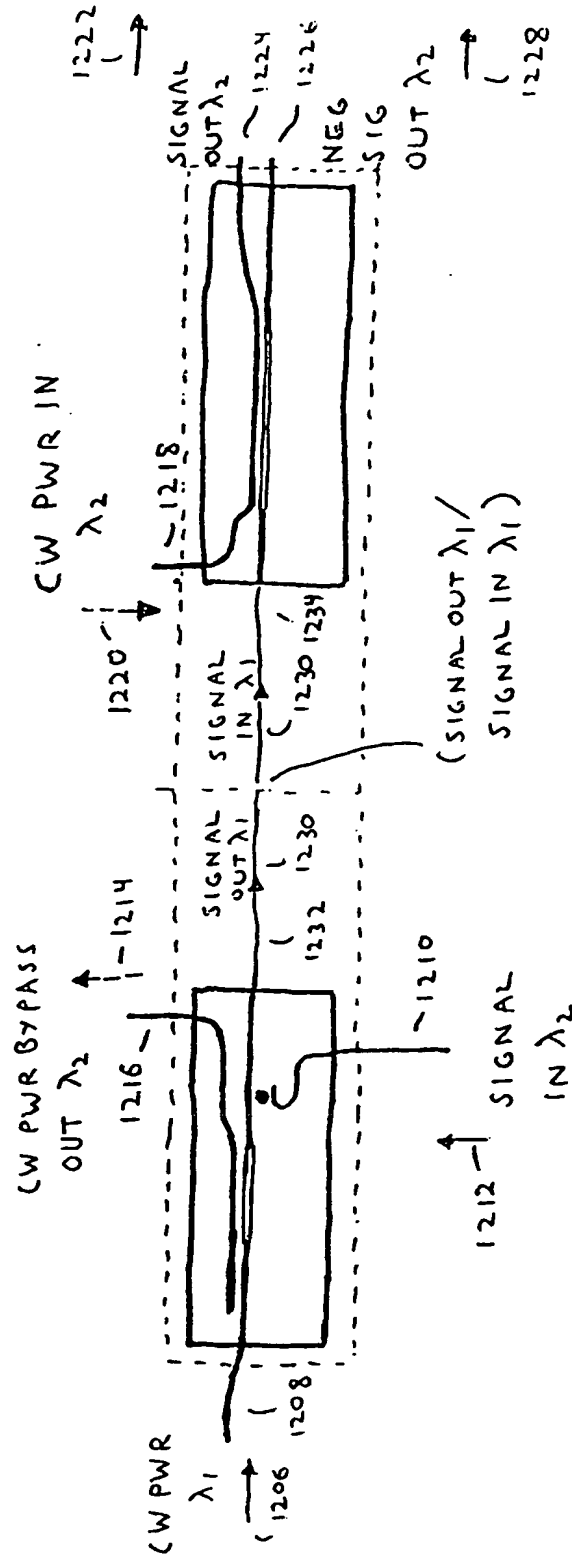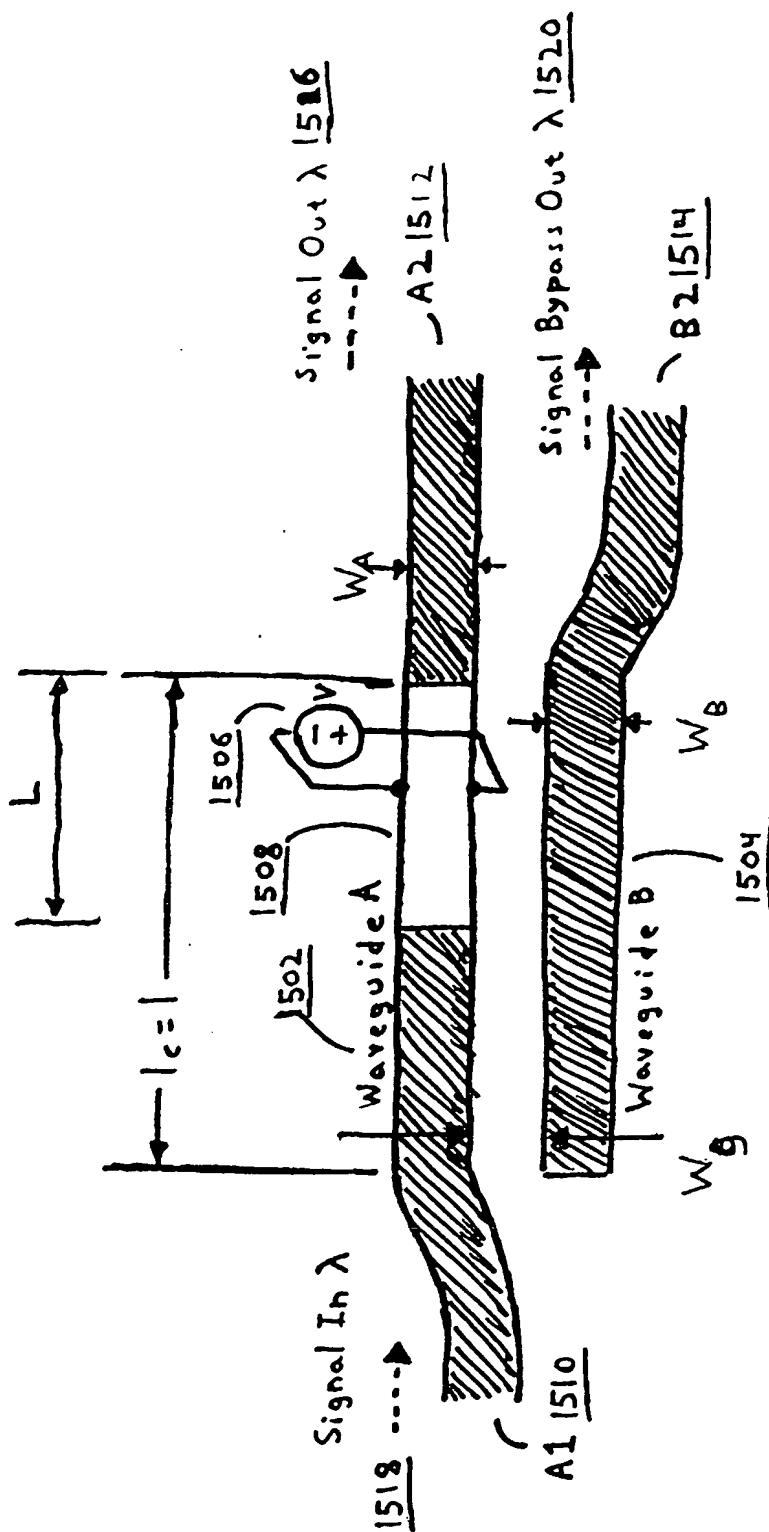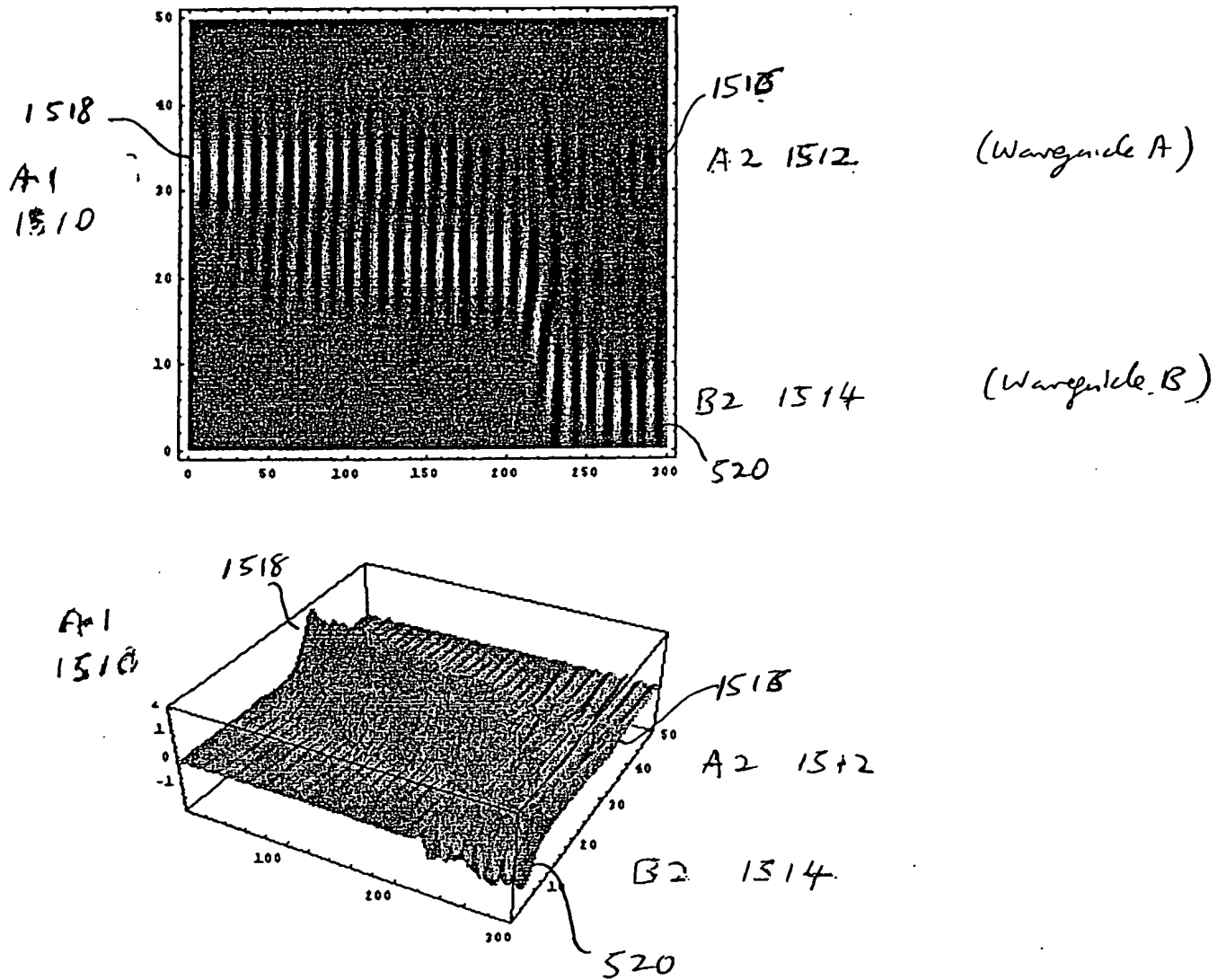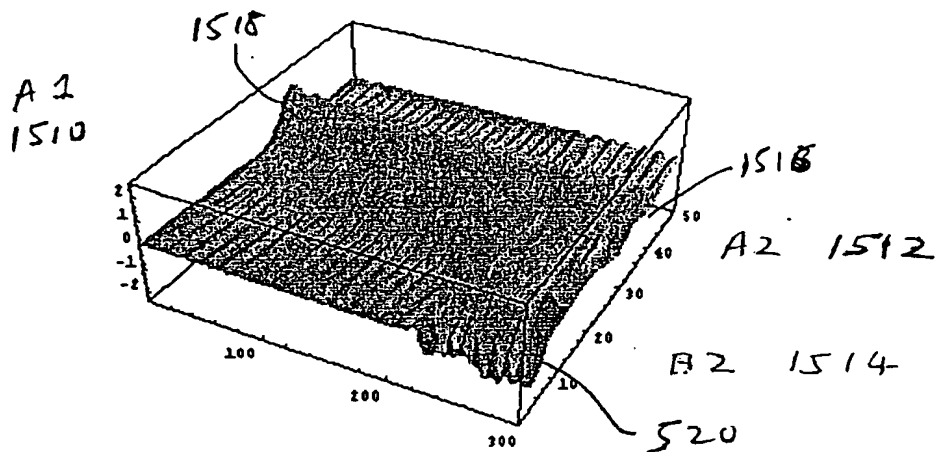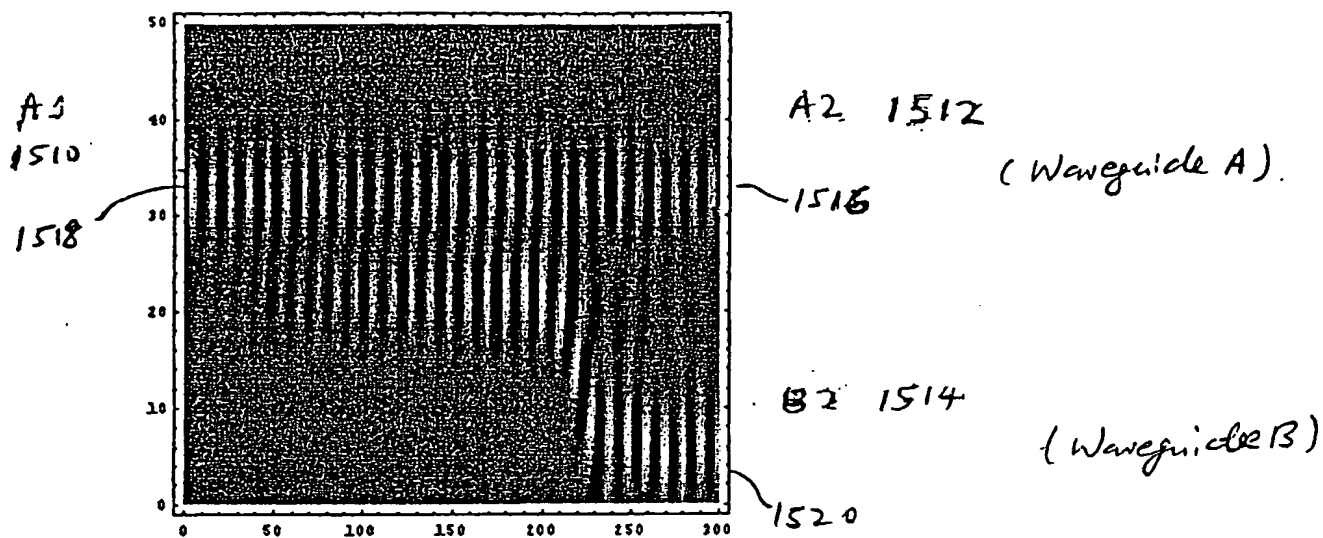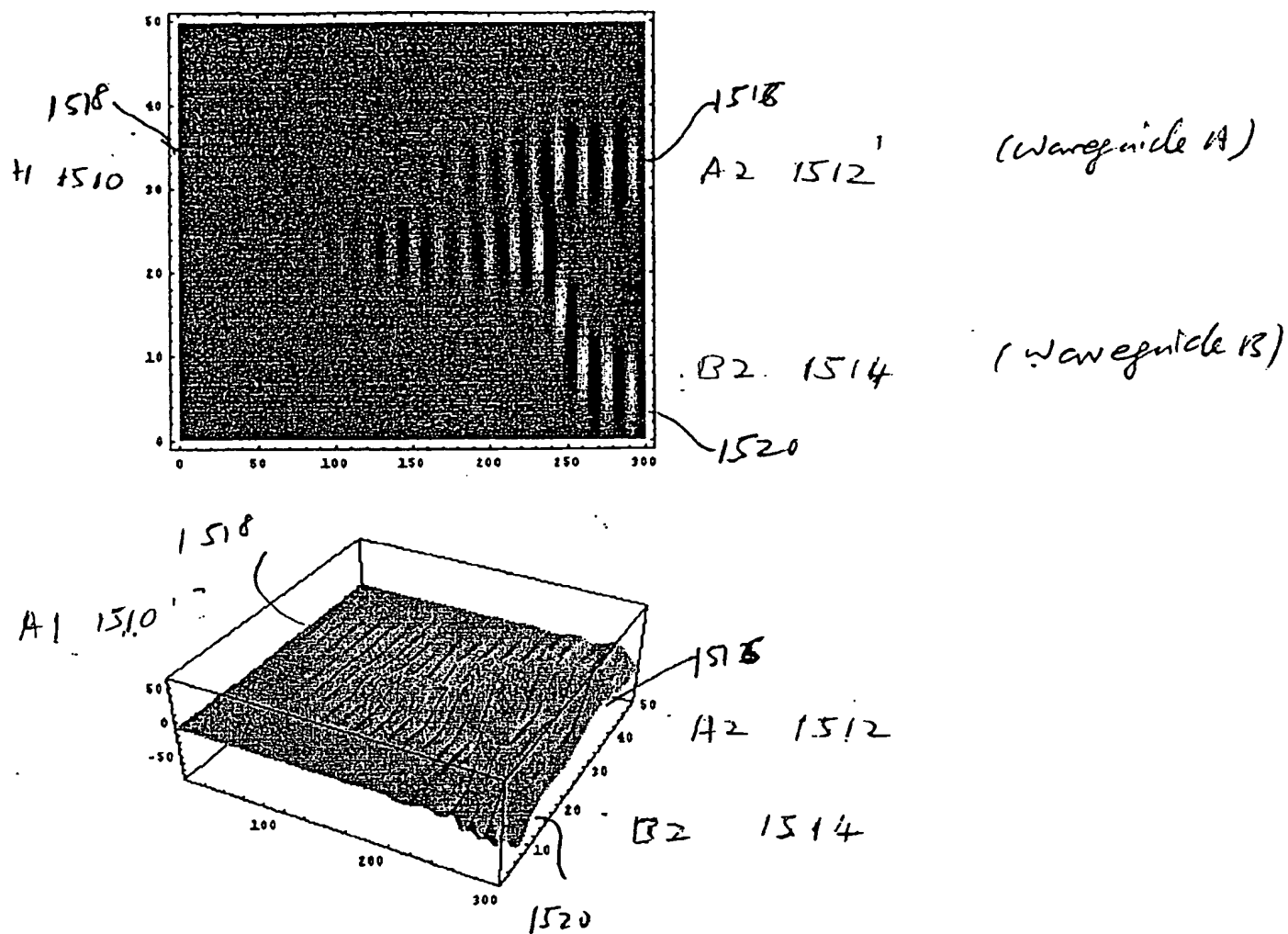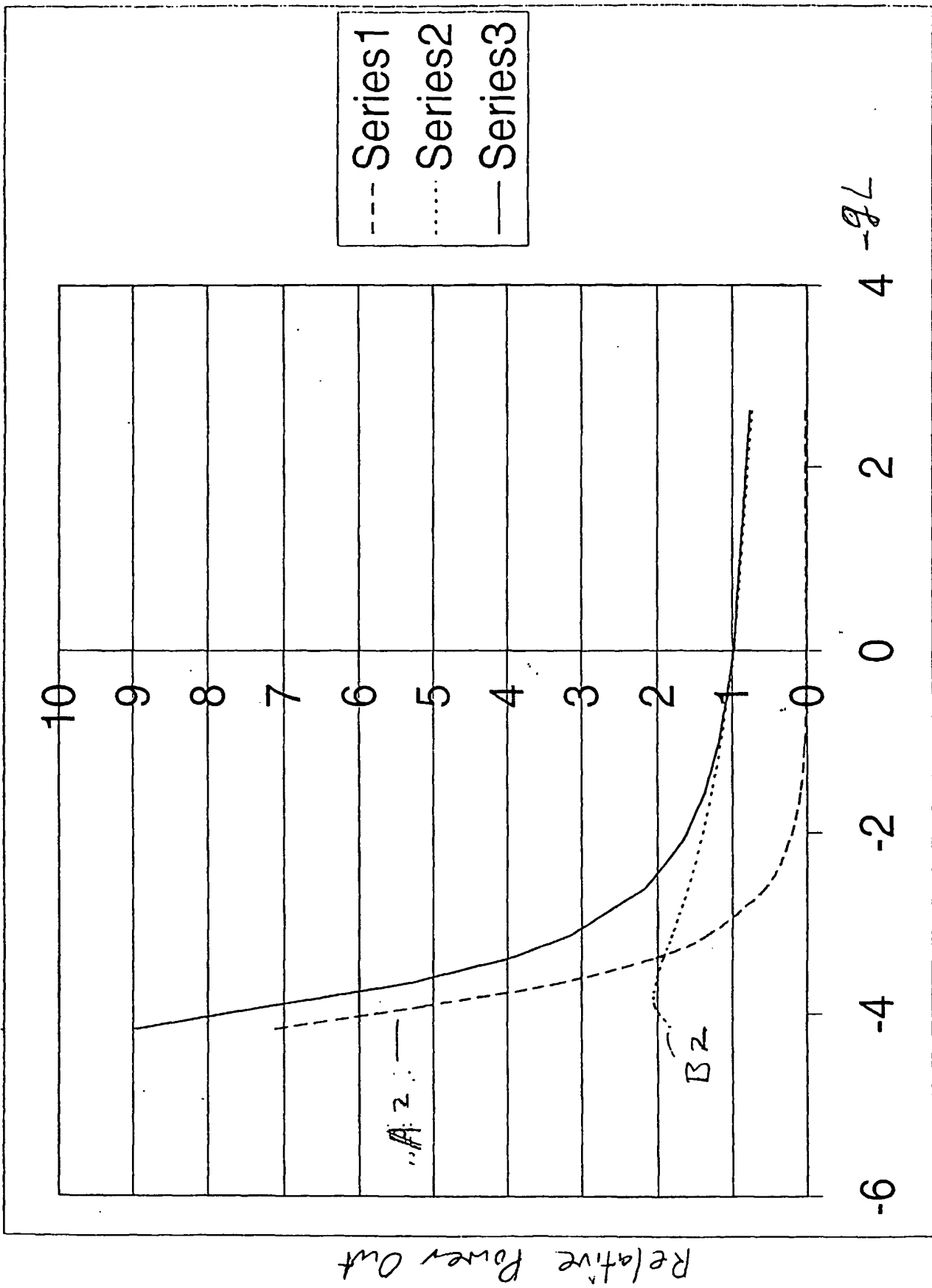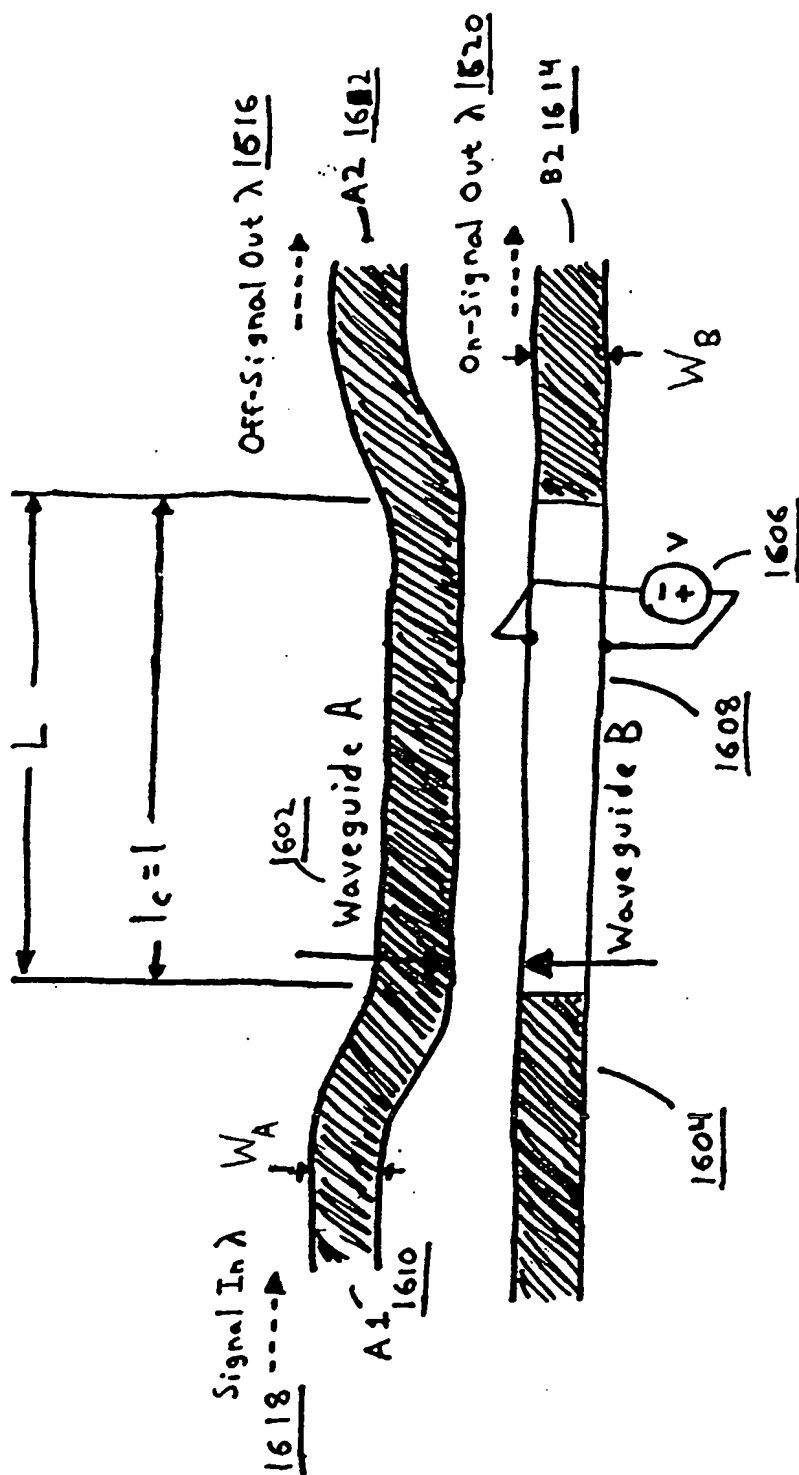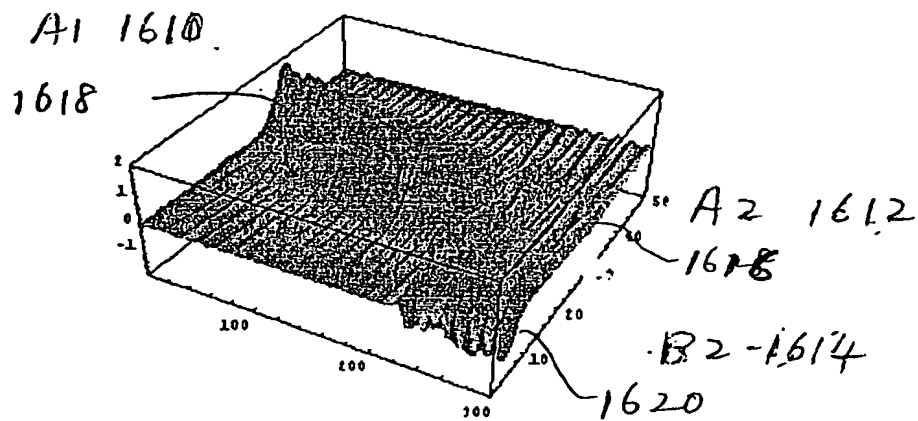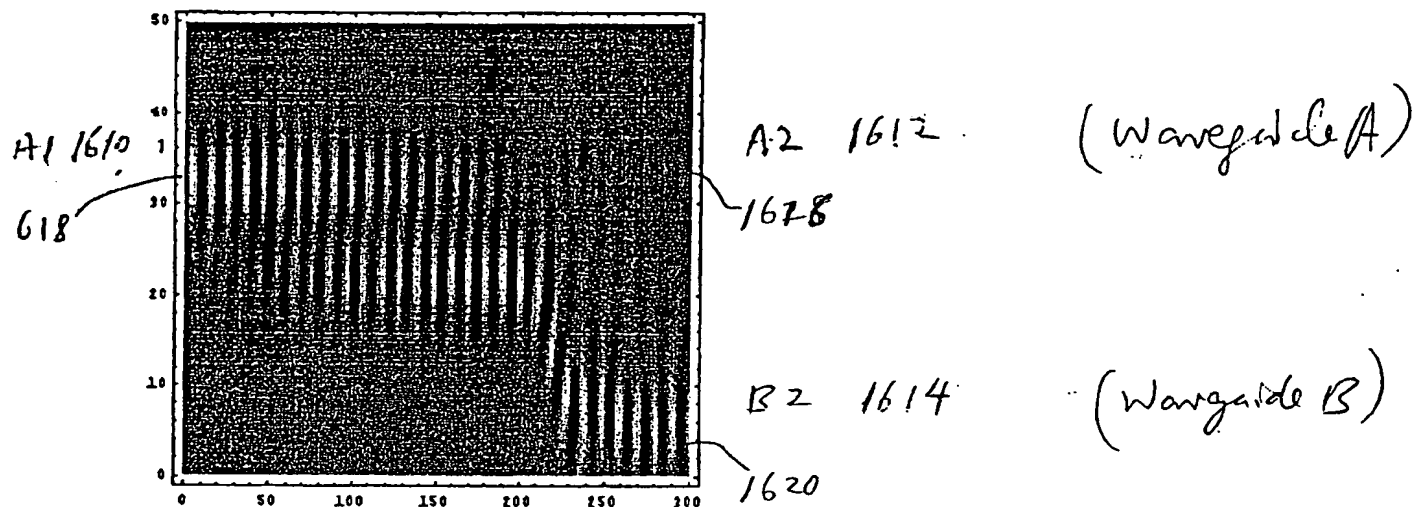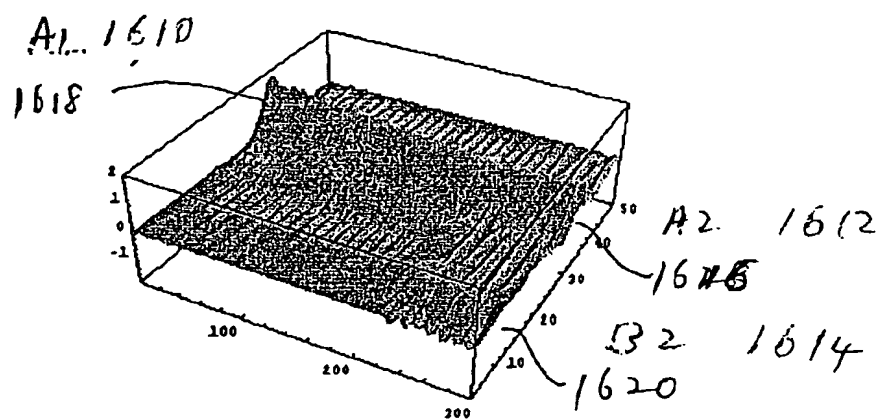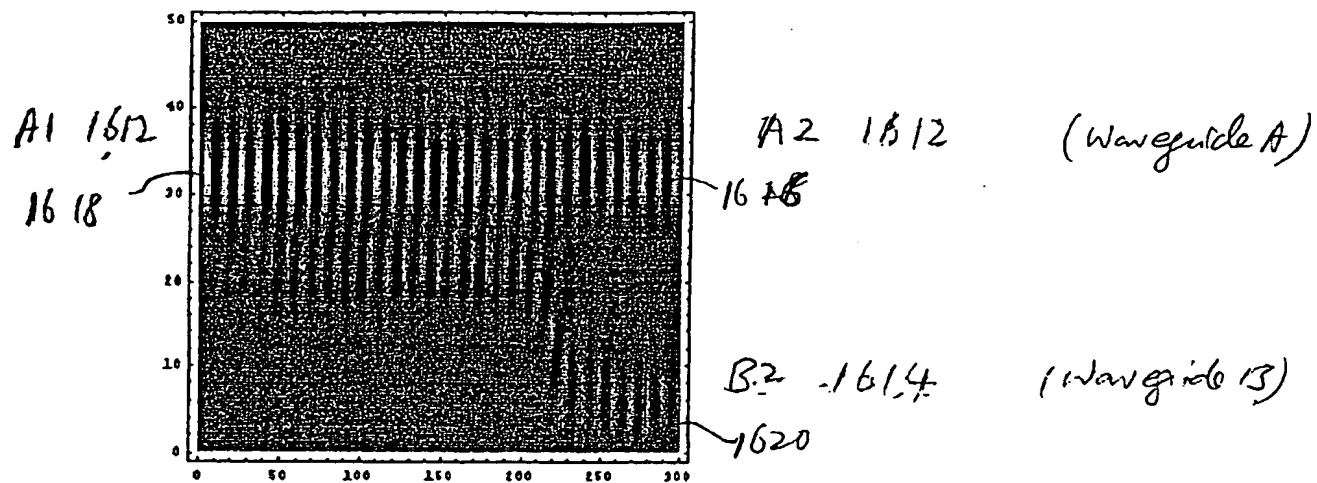
FIG 14B

FIG. 14C

FIG 14D

FIG. 15

FIG. 15A

A1 →

→ A2

→ B2

→ A2

→ B2
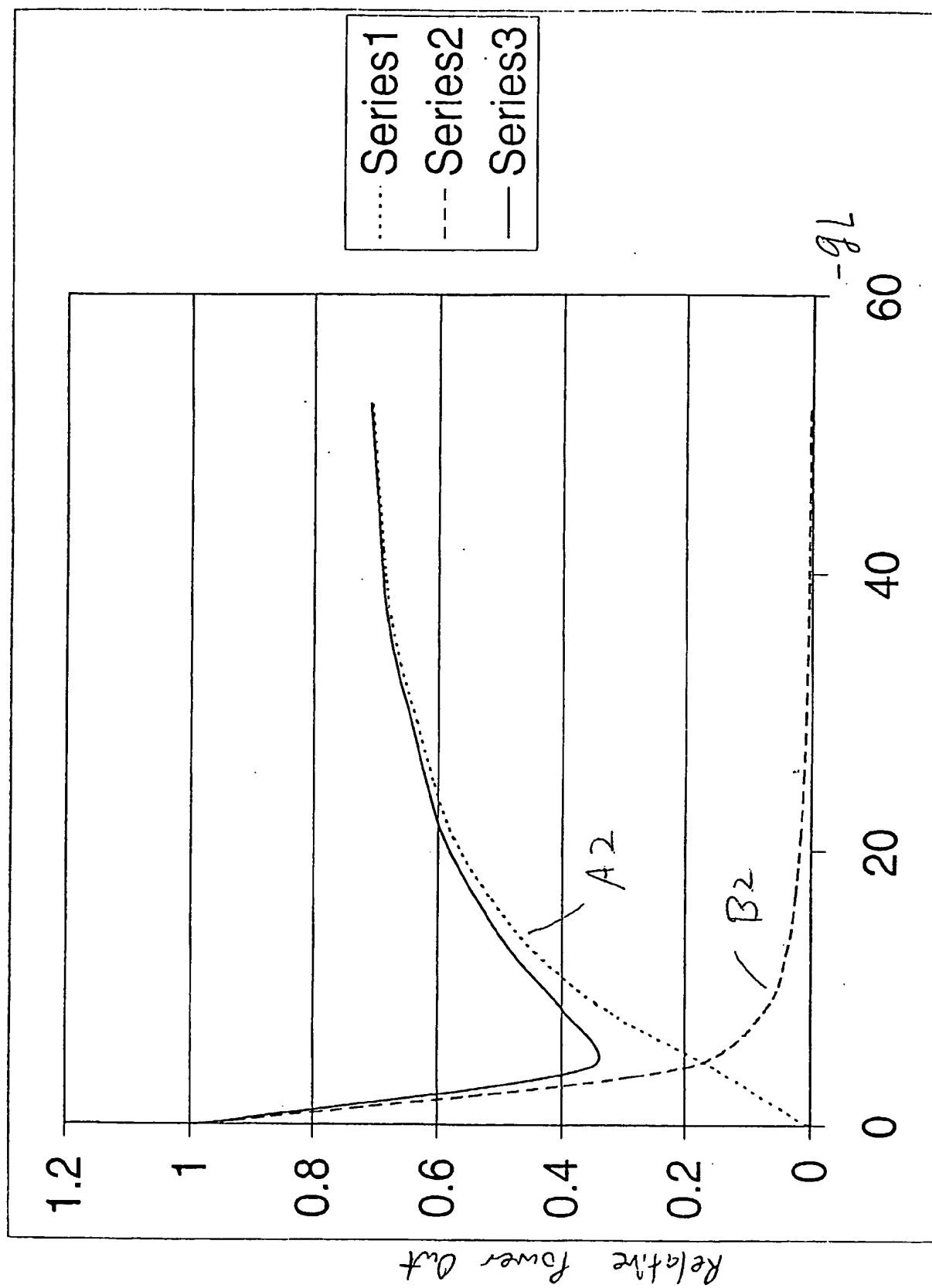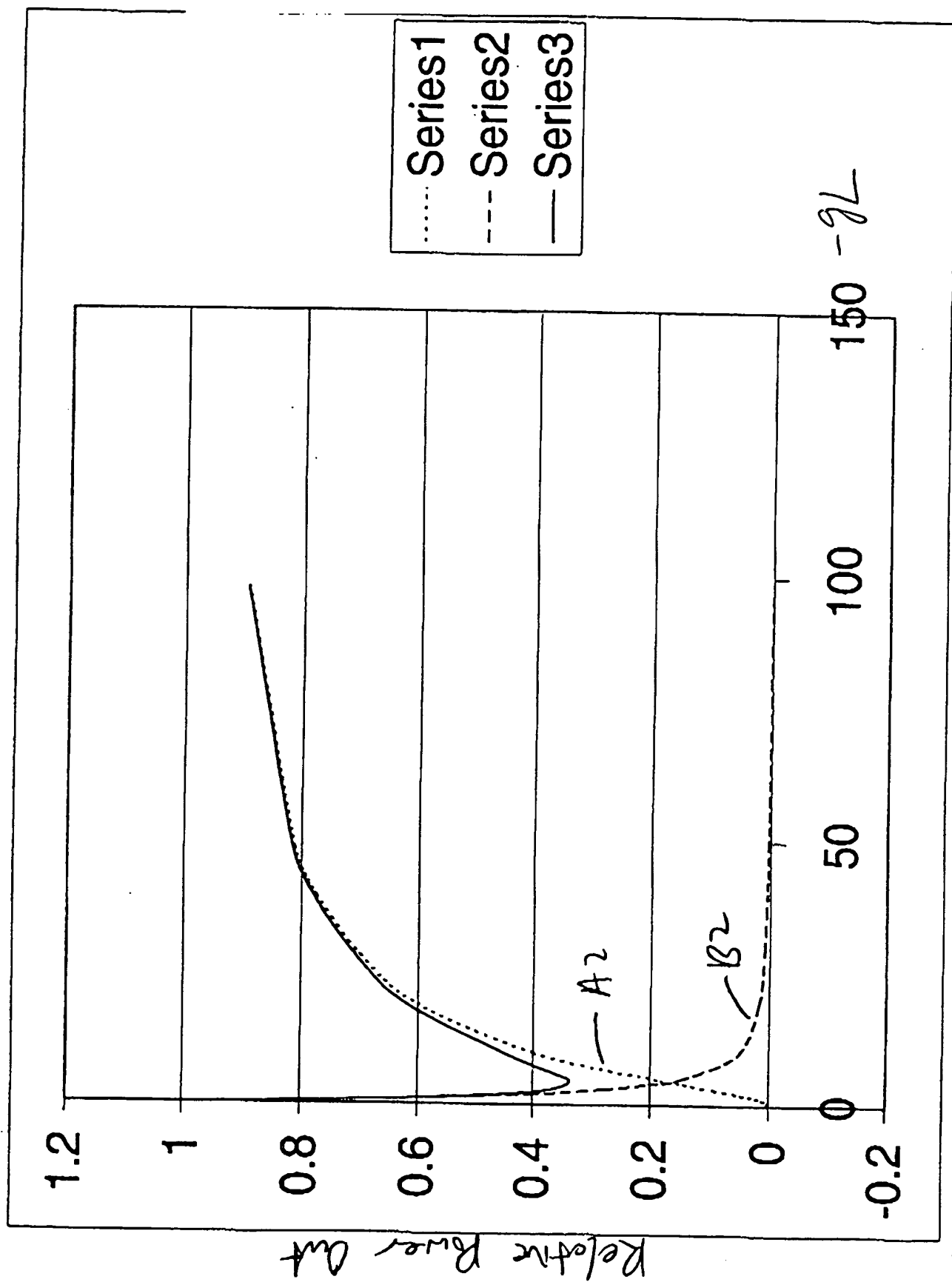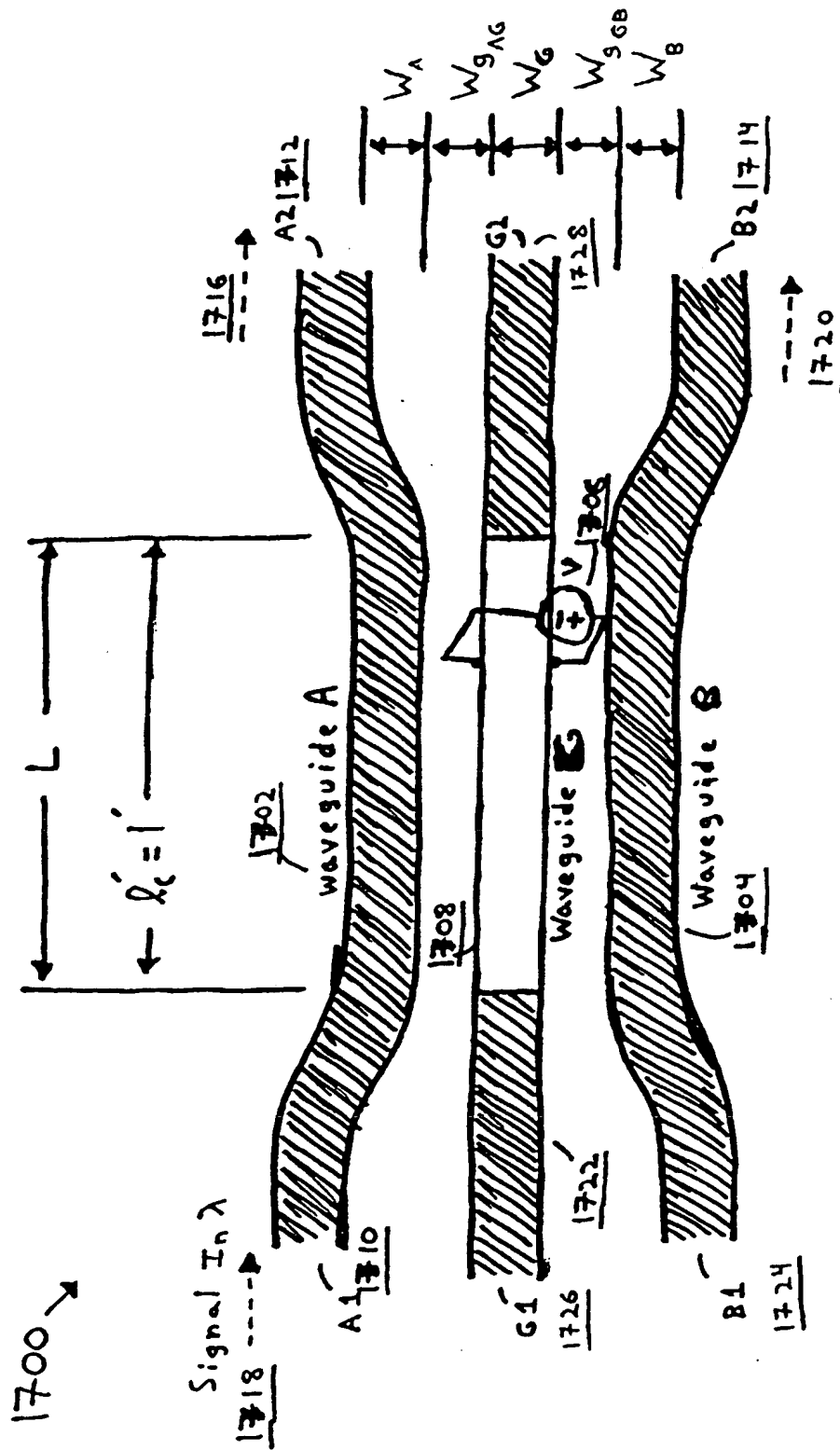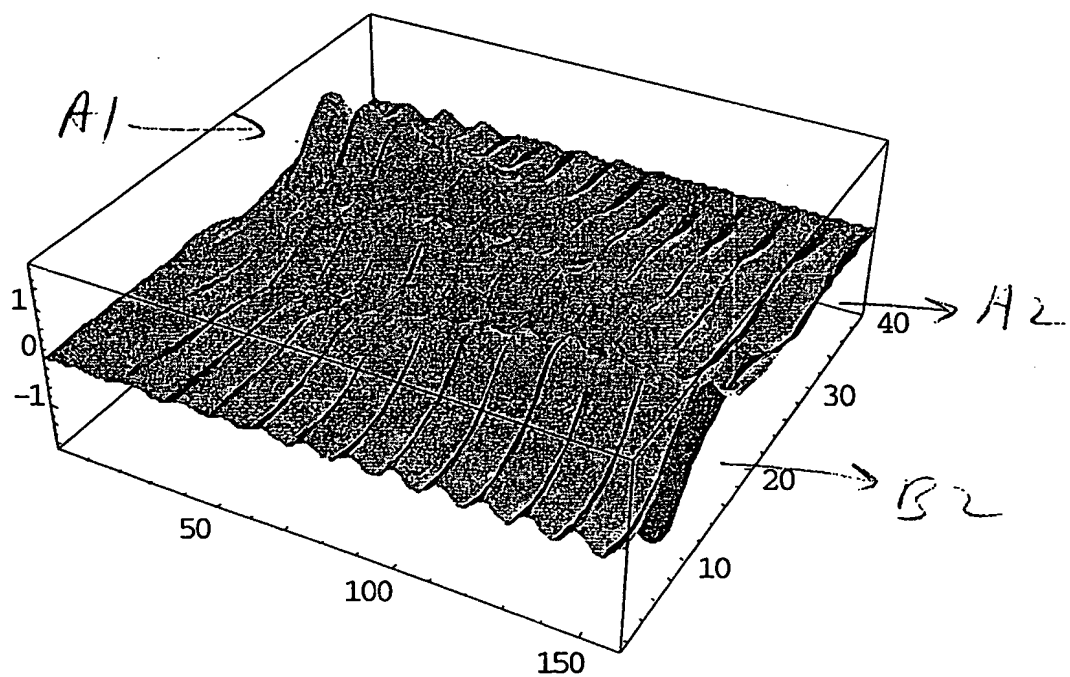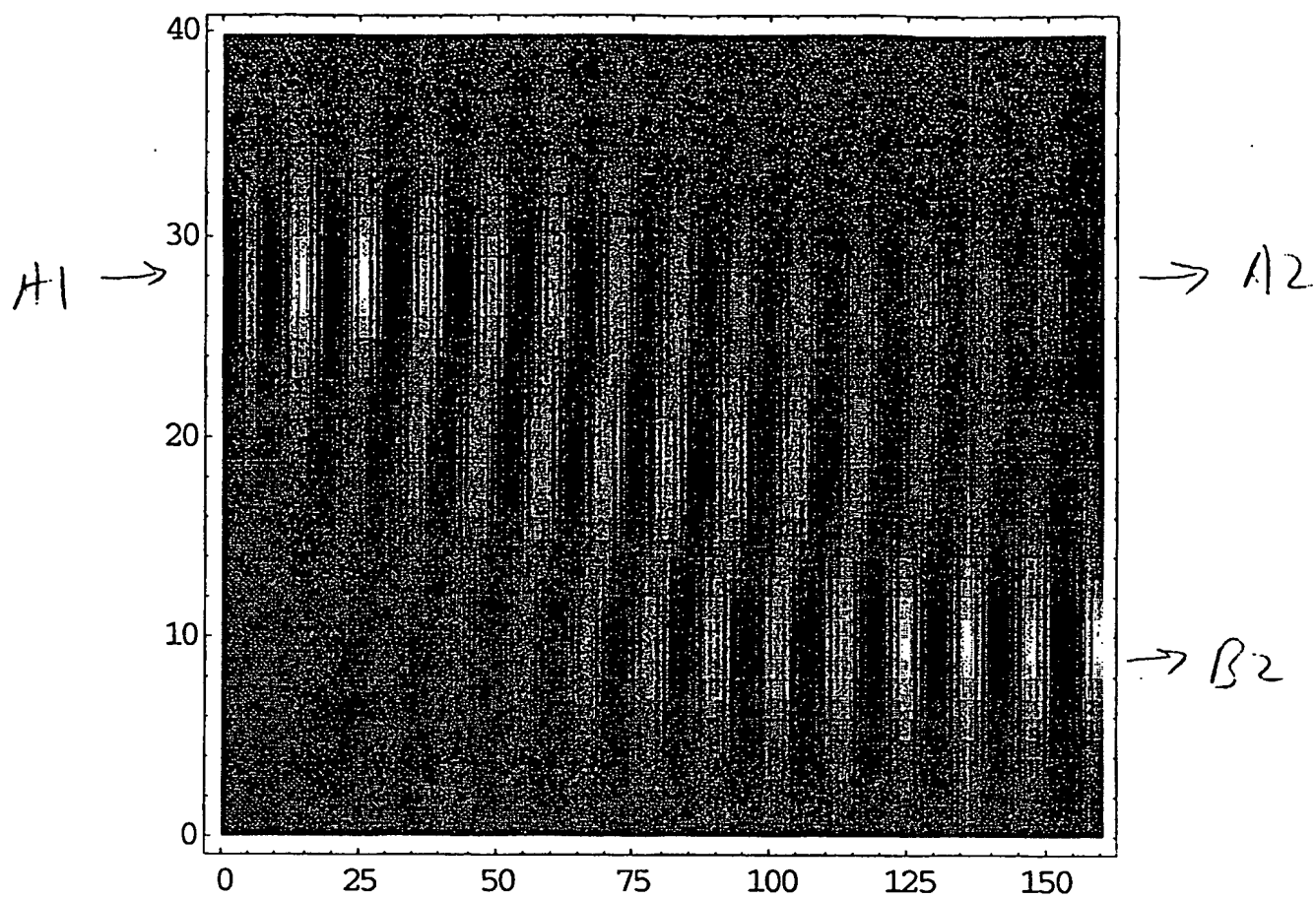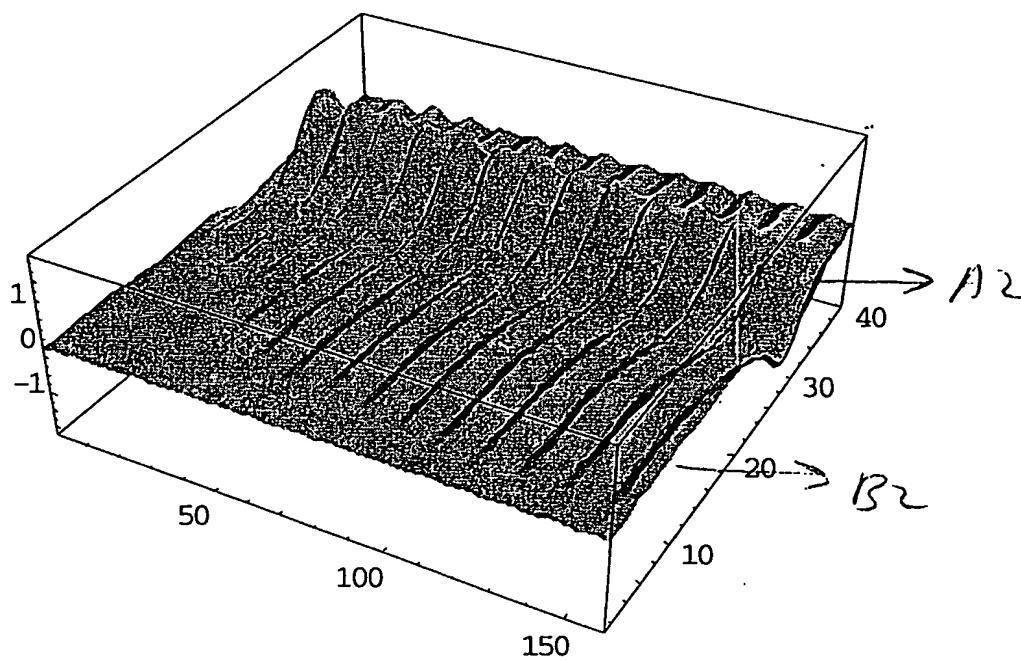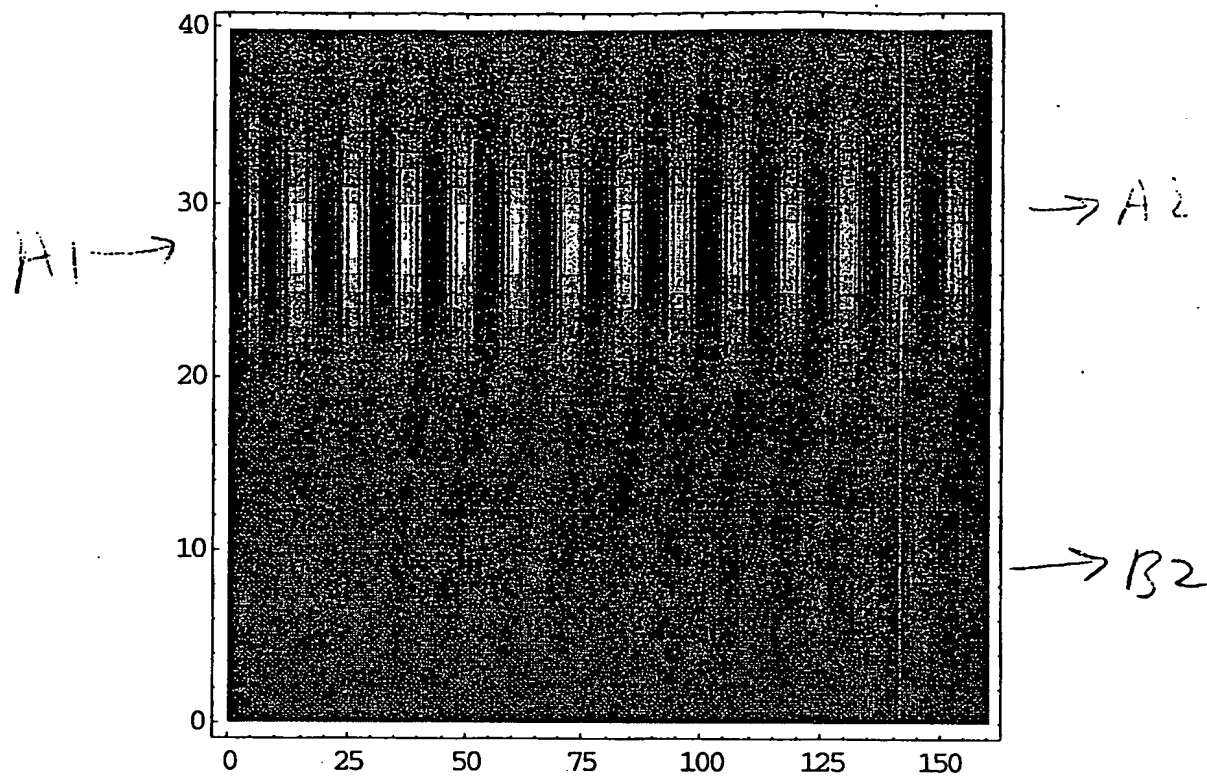
FIG 15B

FIG. 15C

FIG 15D

FIG. 16
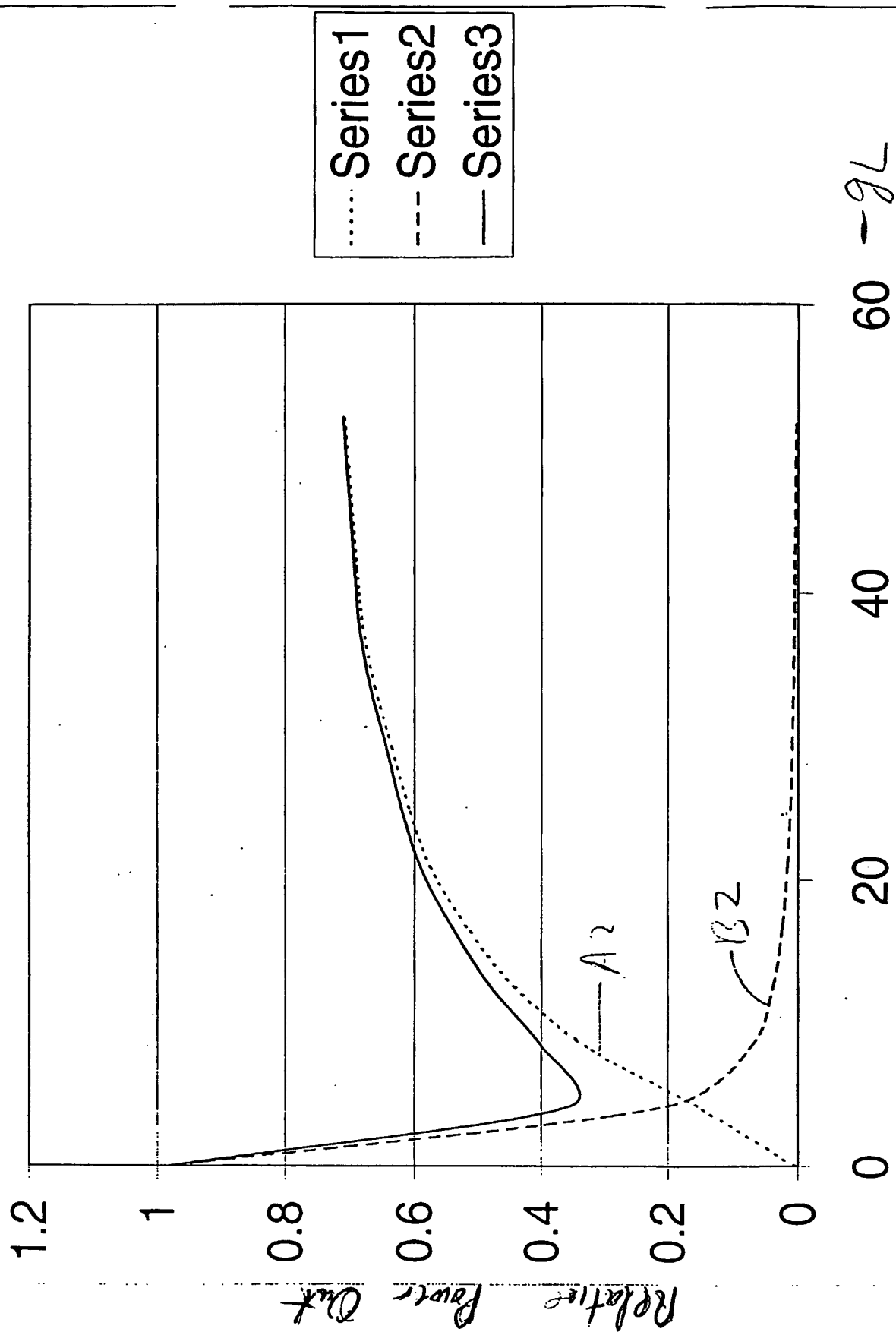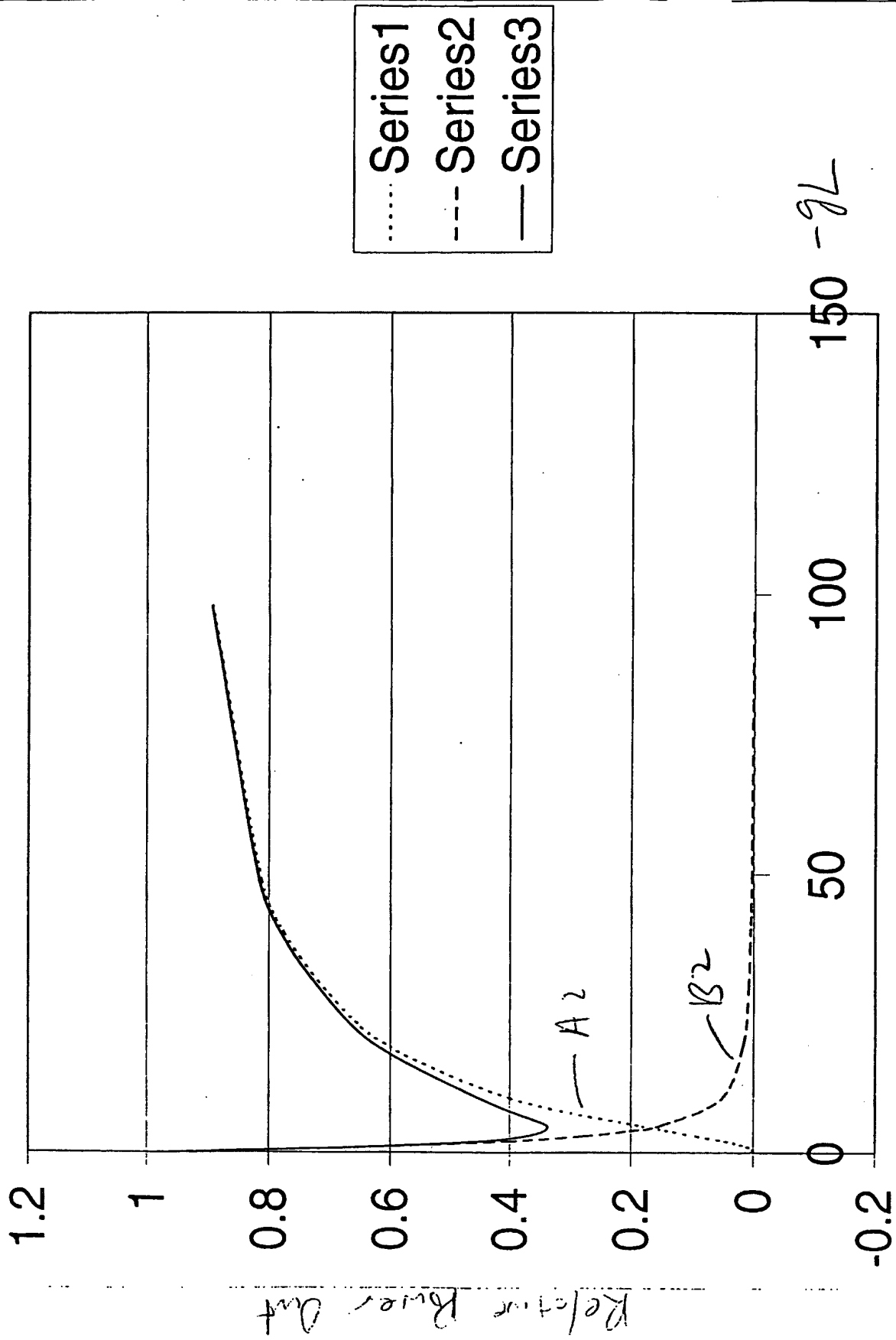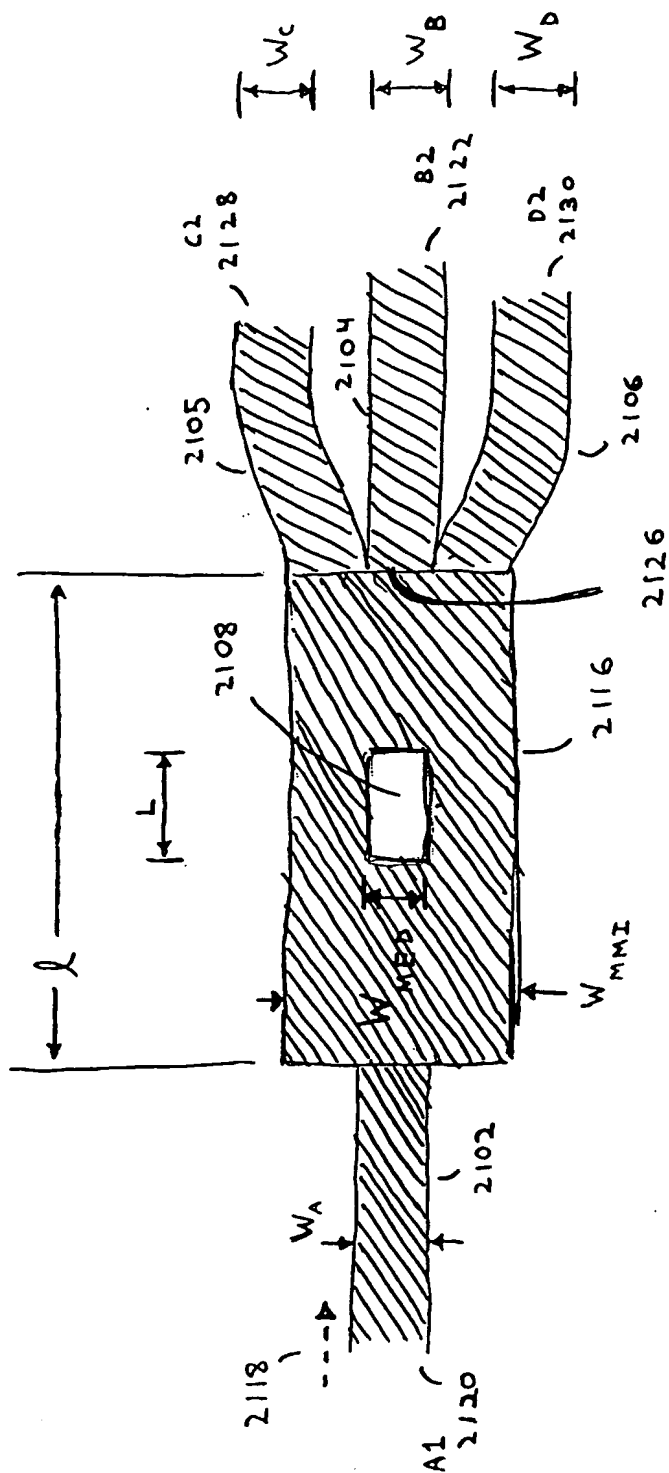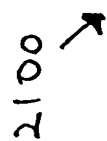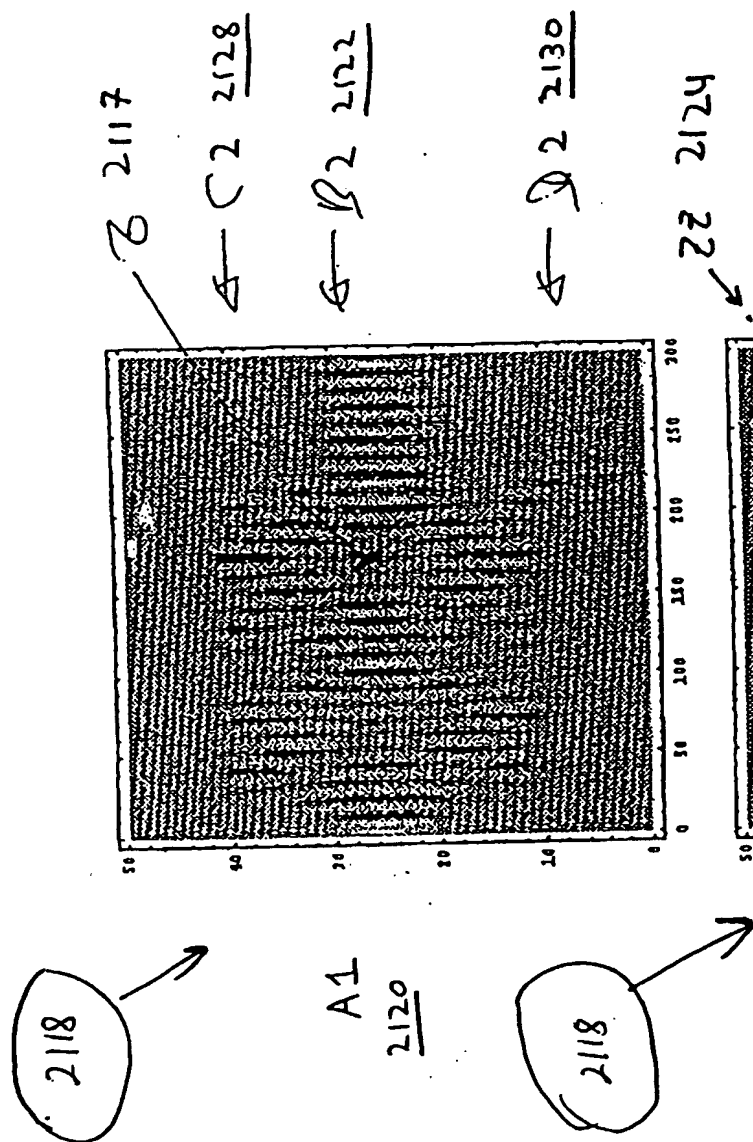
FIG. 17A

FIG. 17B

FIG. 18

FIG. 19A

A1 →

→ A2

→ B2

→ A2

→ B2
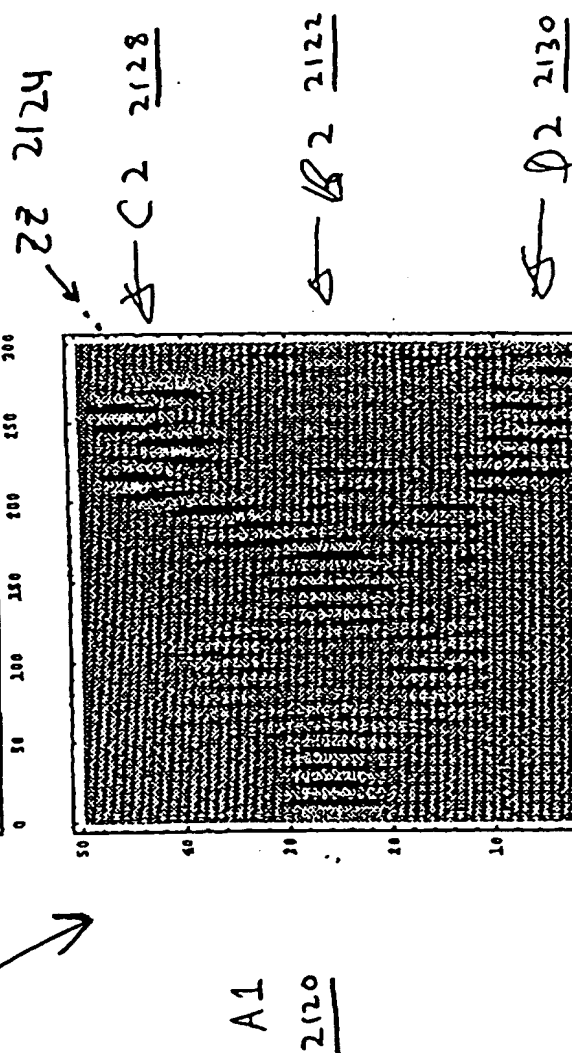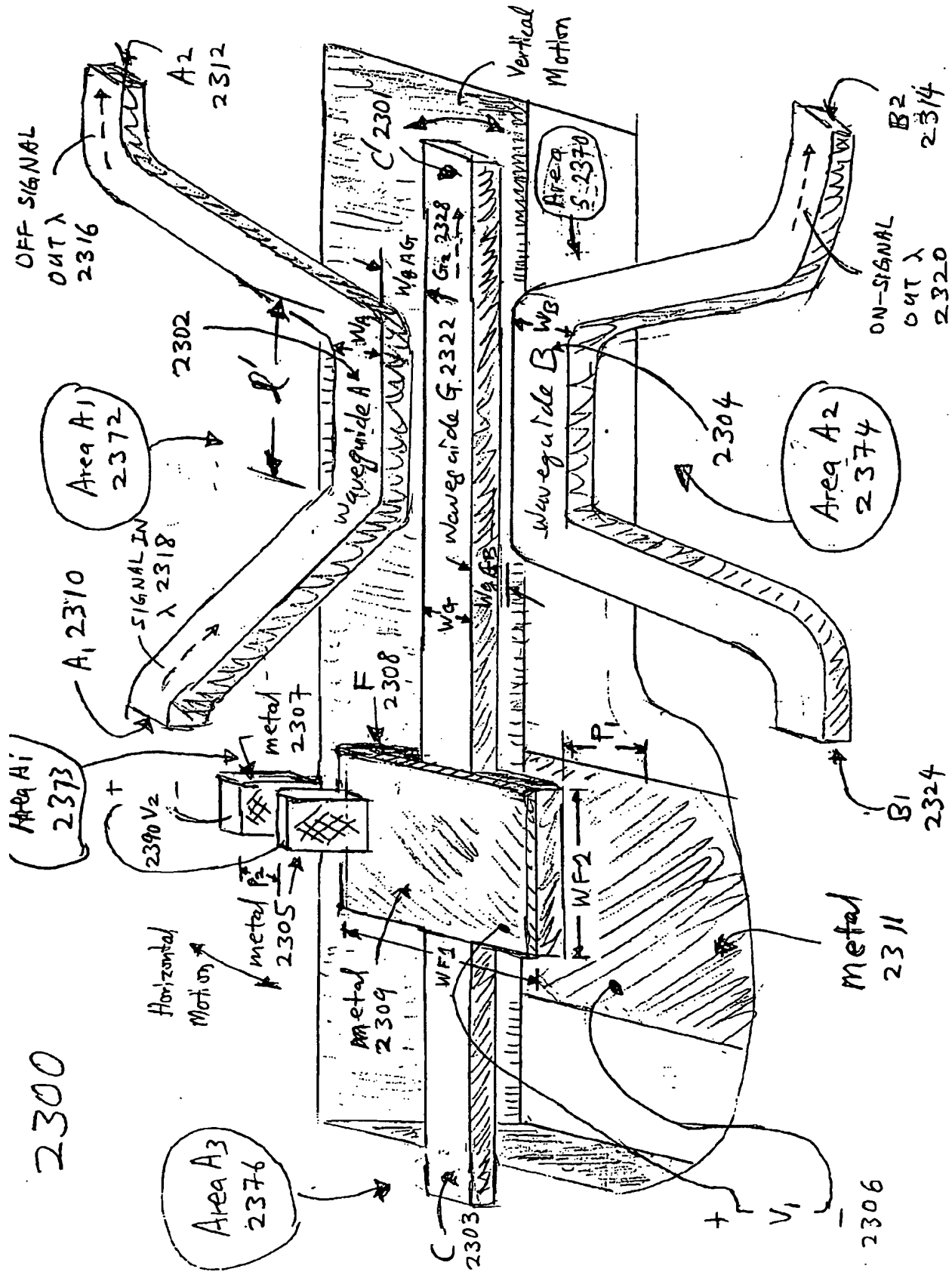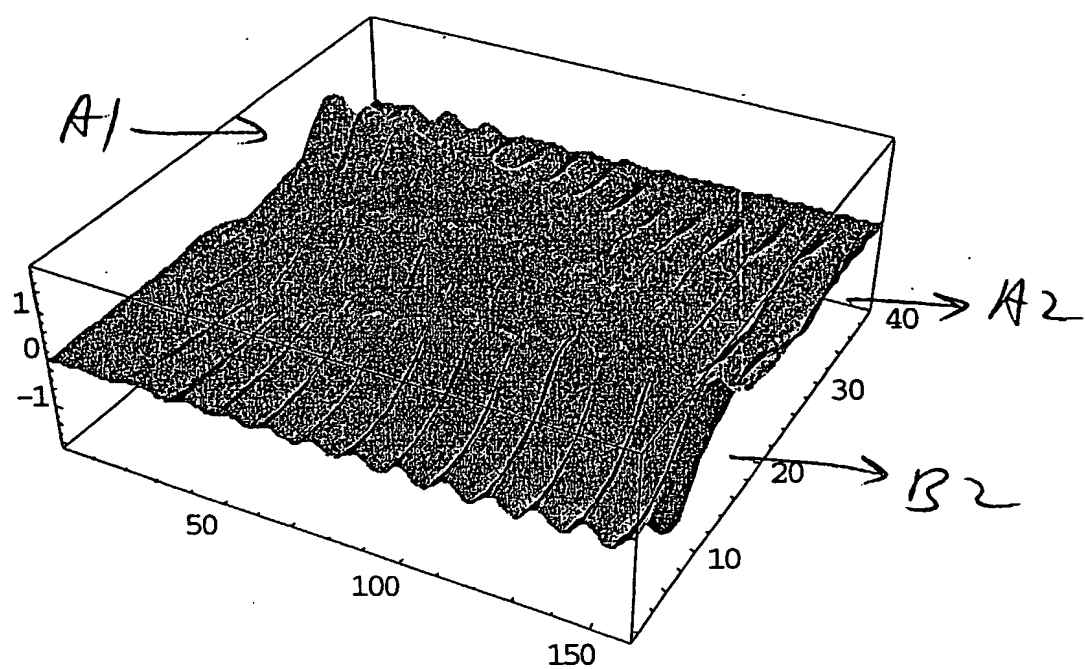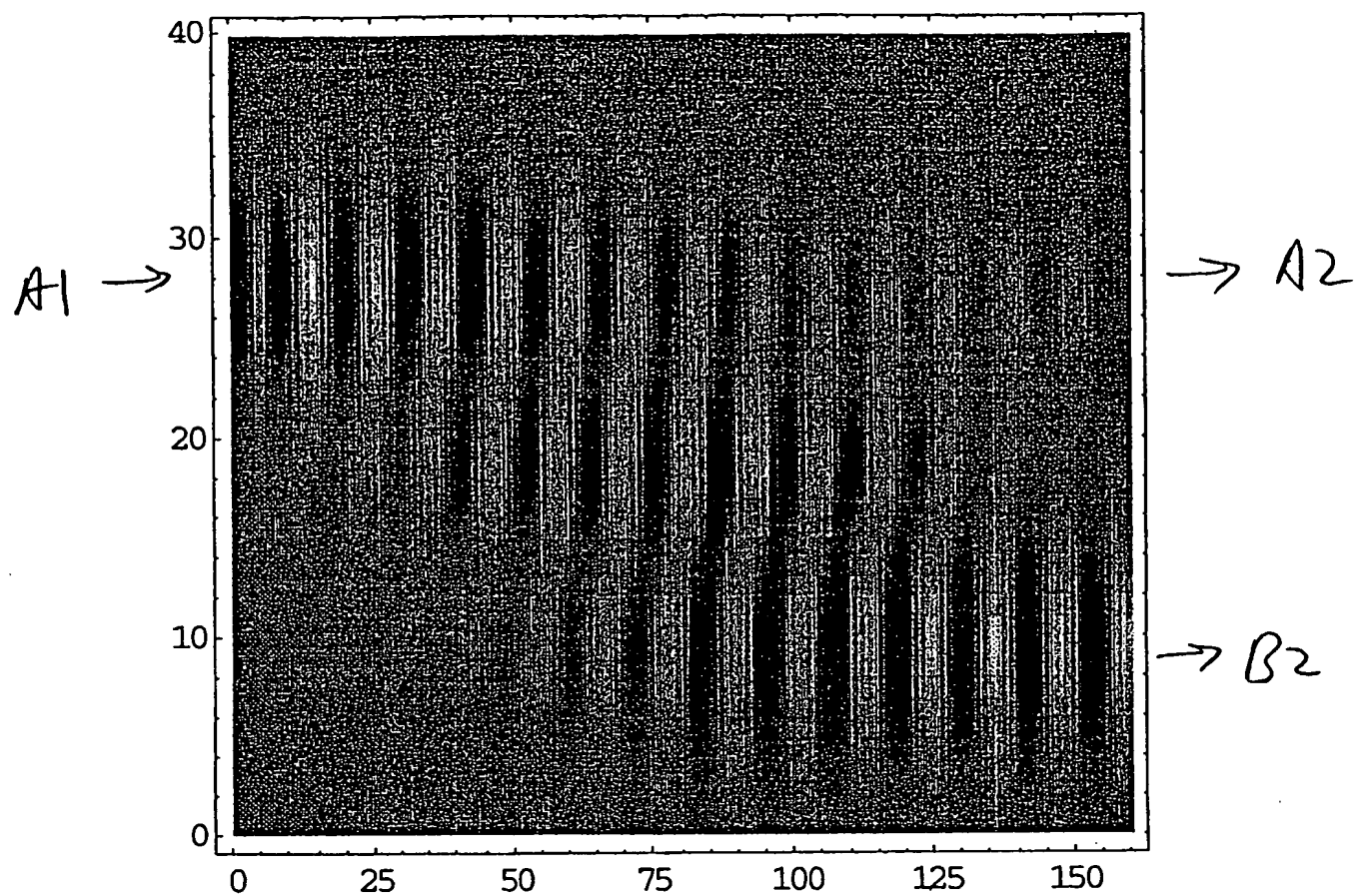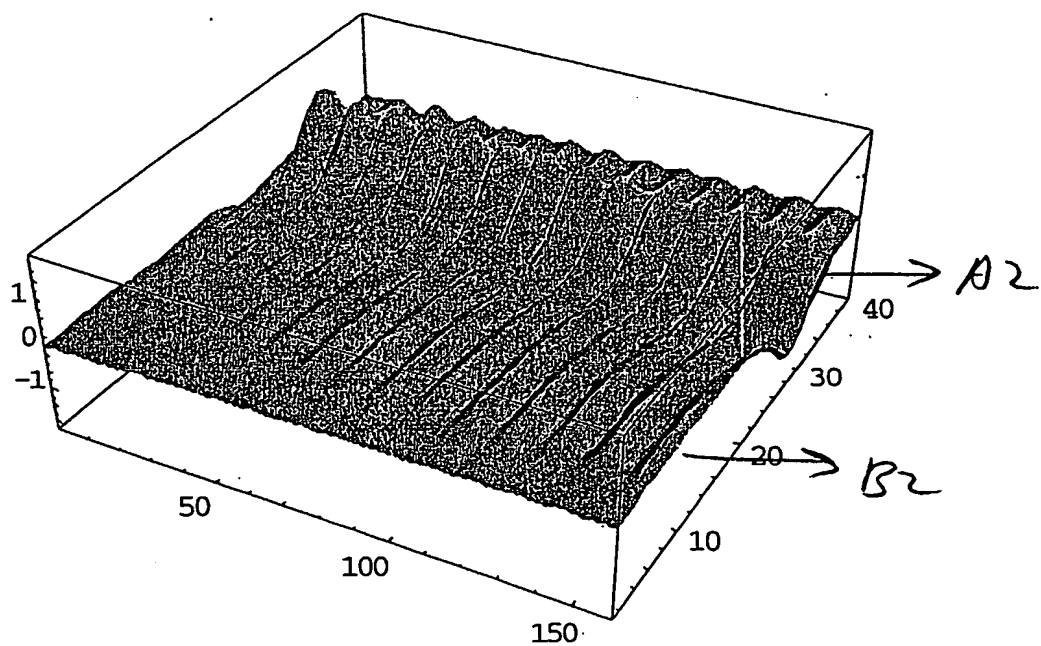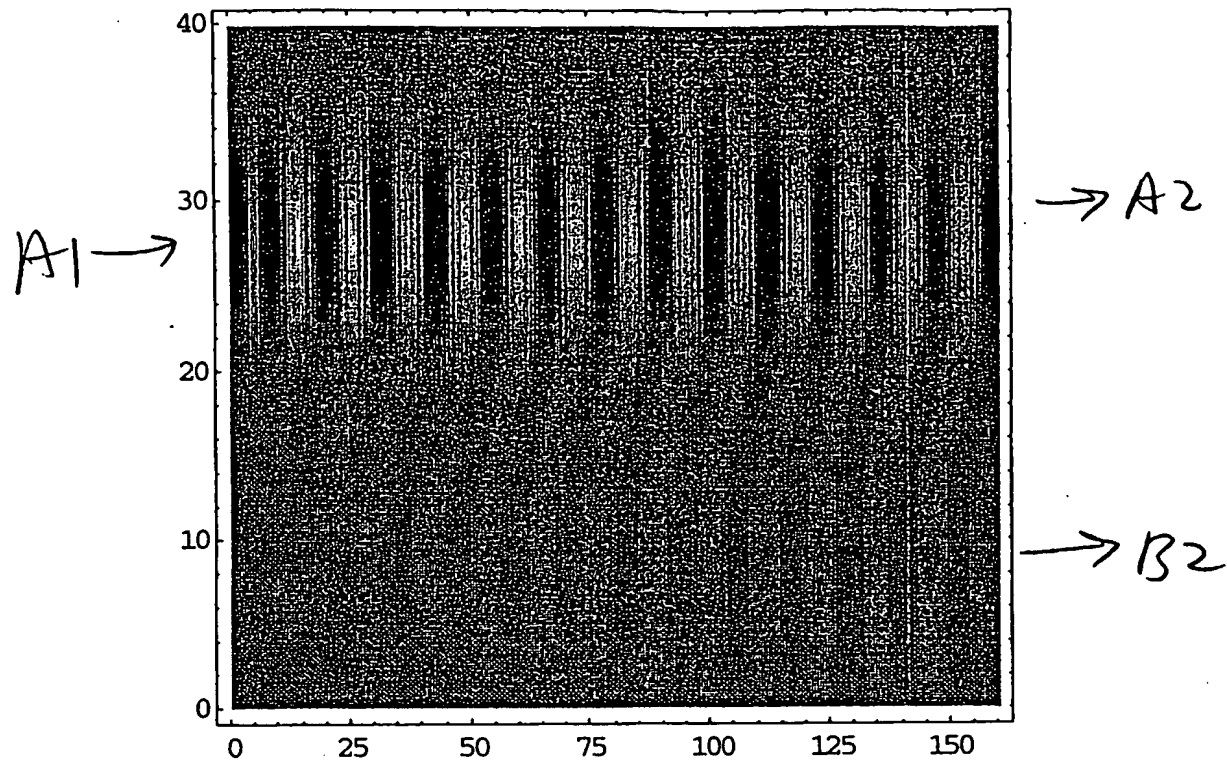
FIG 19B

Undercutting via HF selective etching of SiO_2

FIG 20C.

GaAs etching

FIG. 20B

patterning
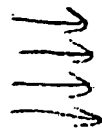
photoresist
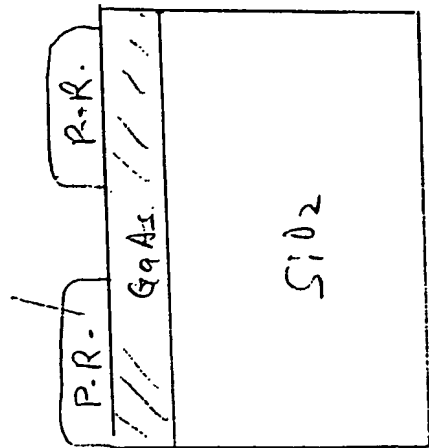
FIG. 20A
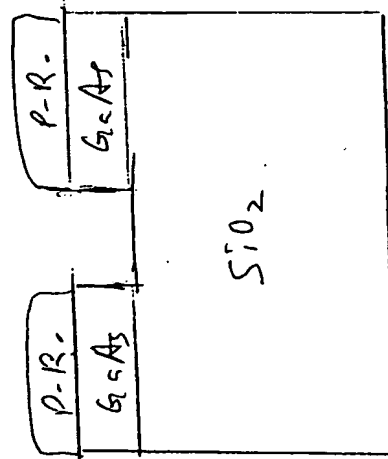
FIG. 20
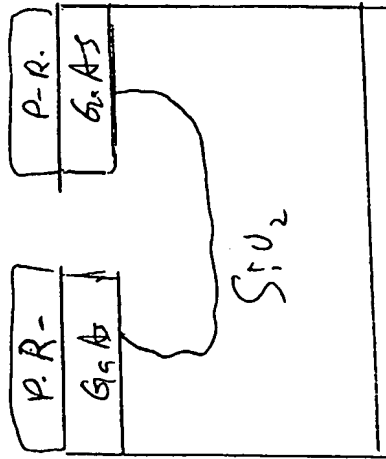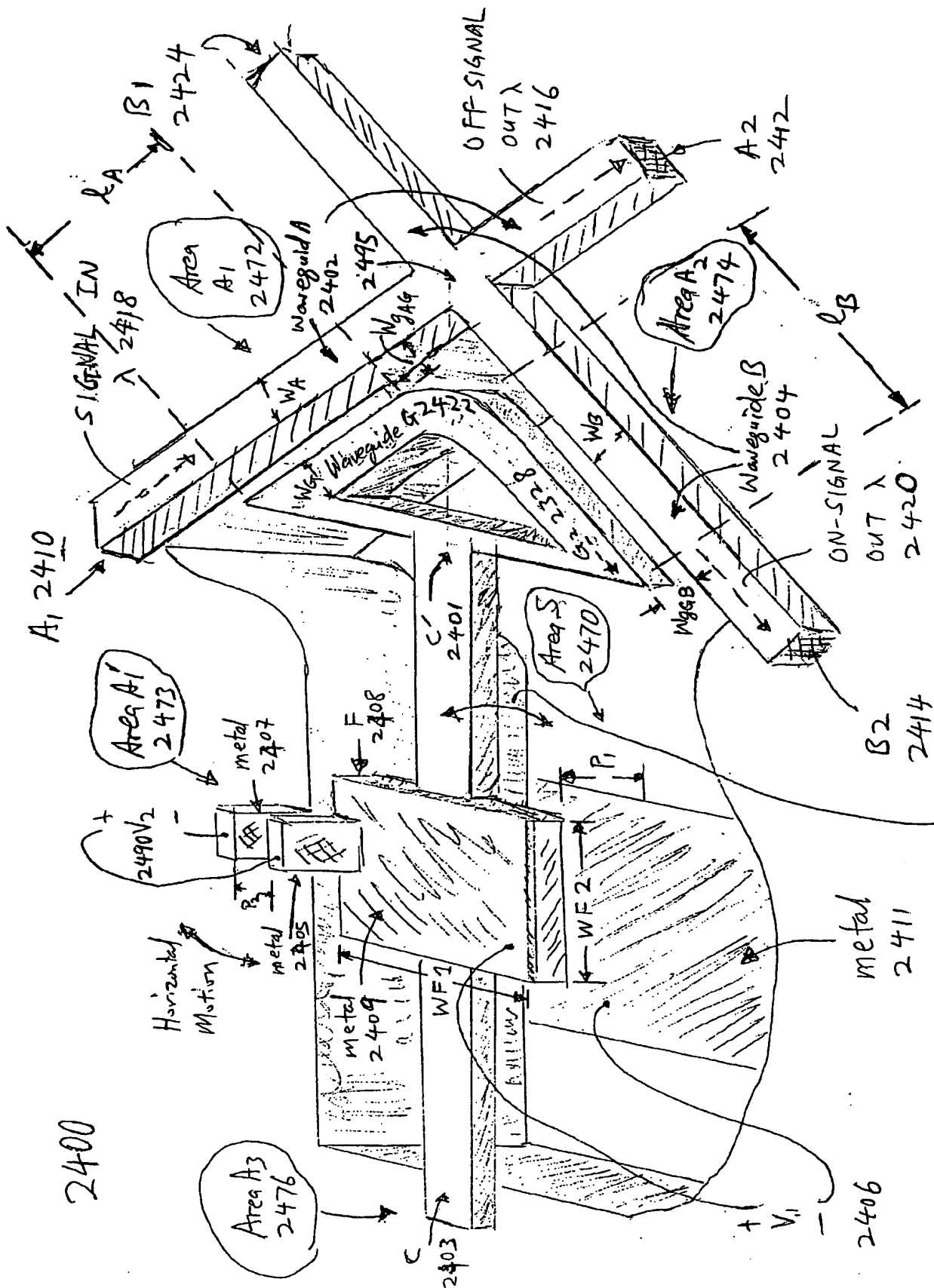
FIG. 21

FIG 22

FIG 23A

2508

2500

FIG. 23B

2500

2508

FIG. 23C

2600
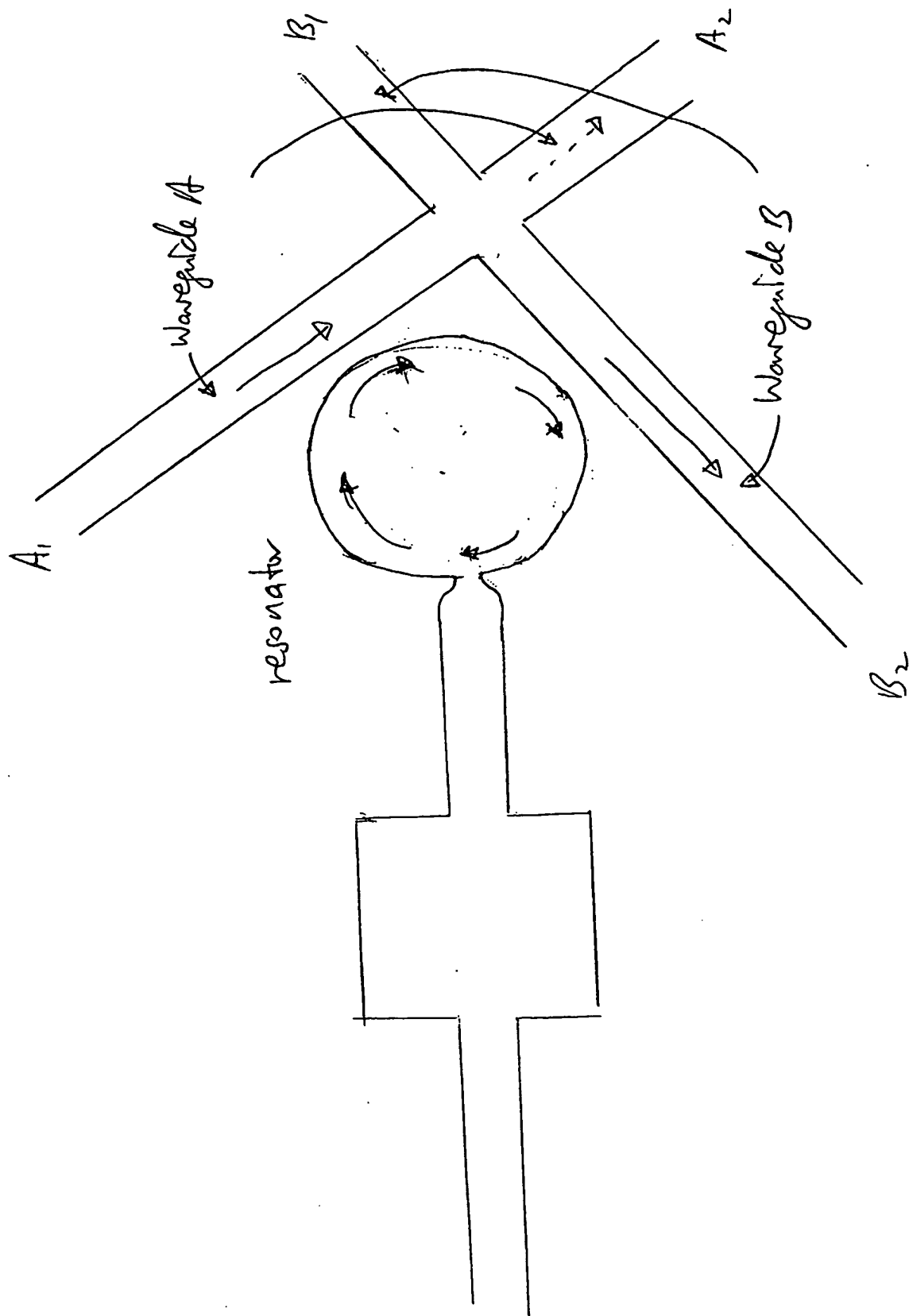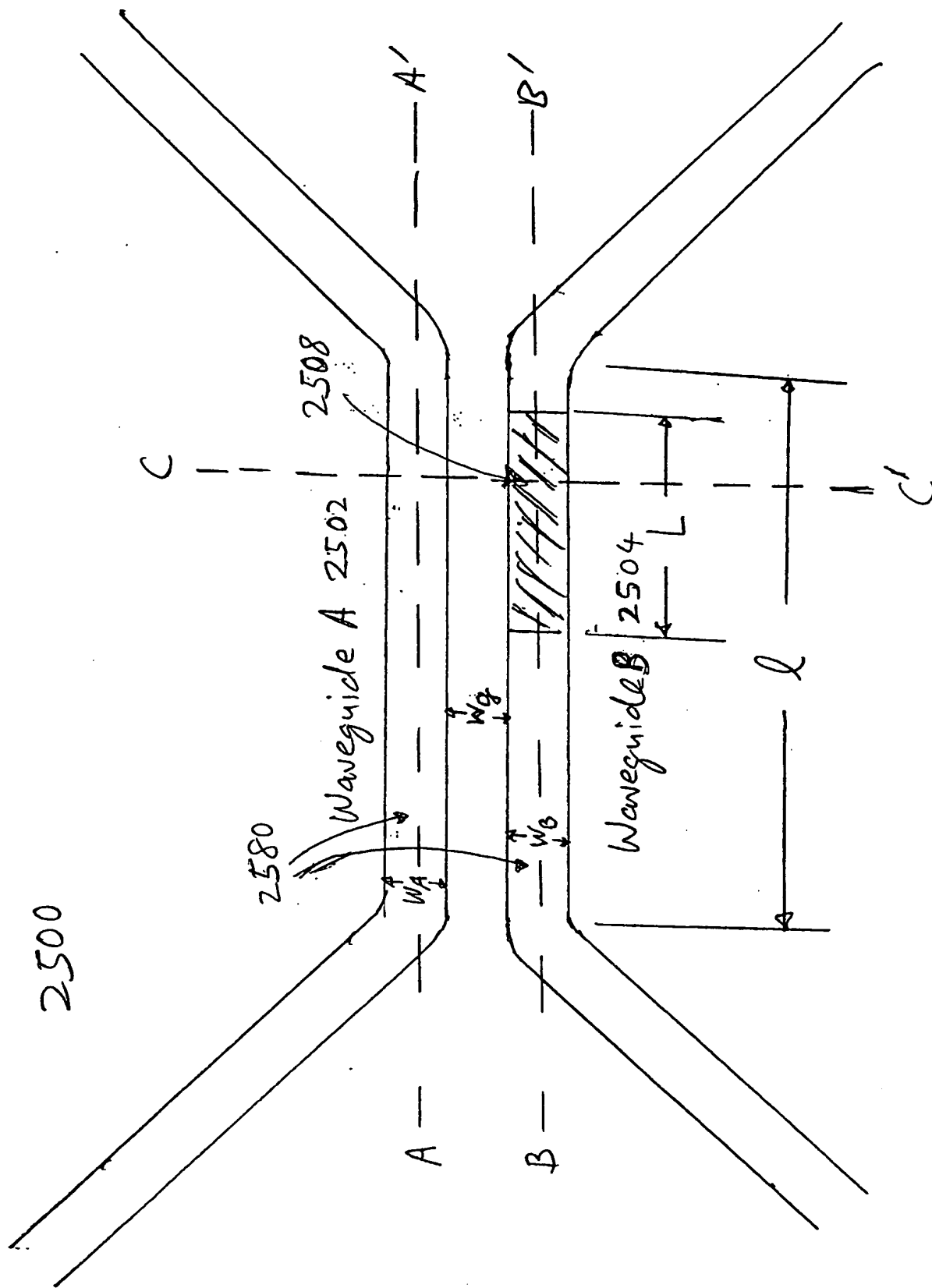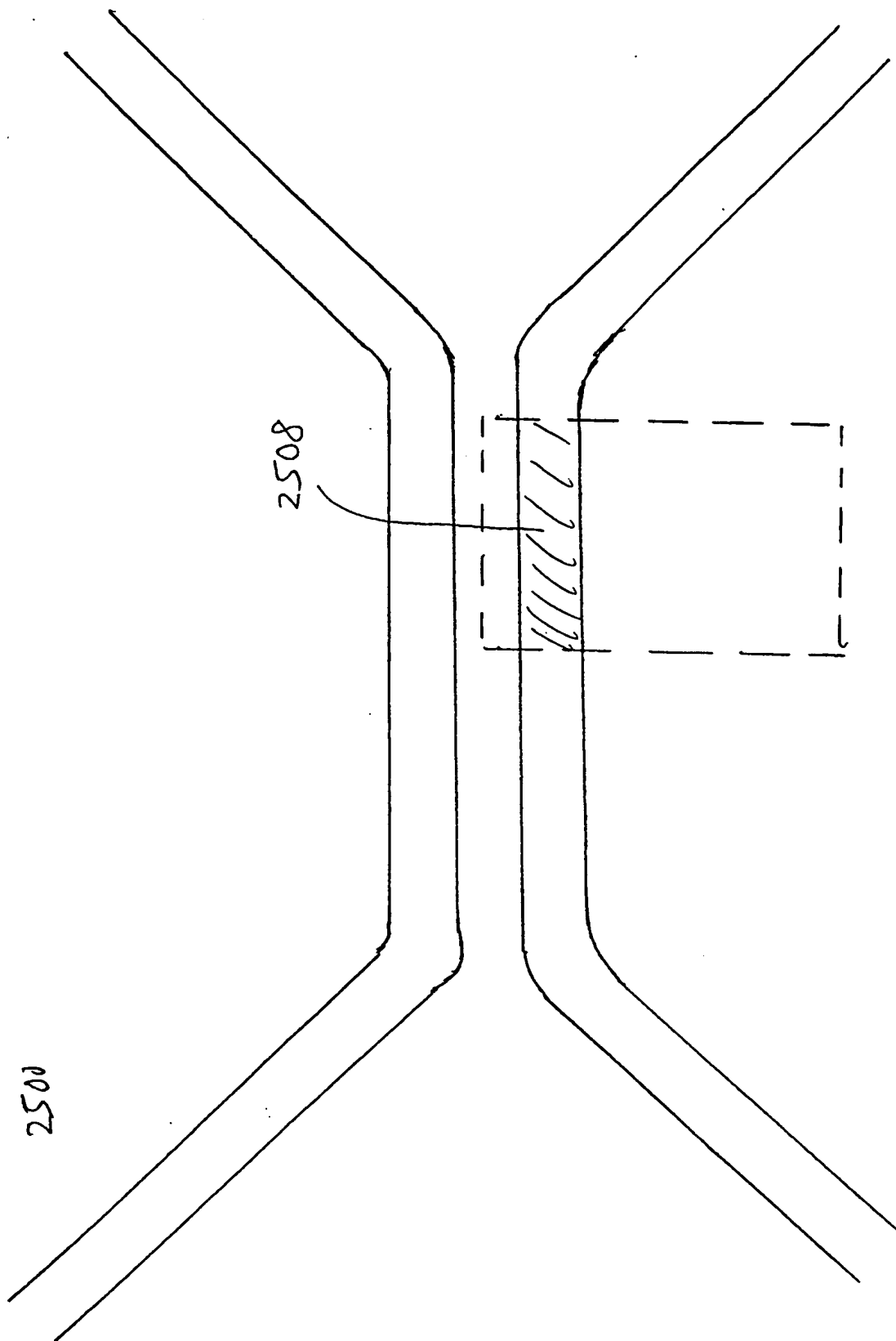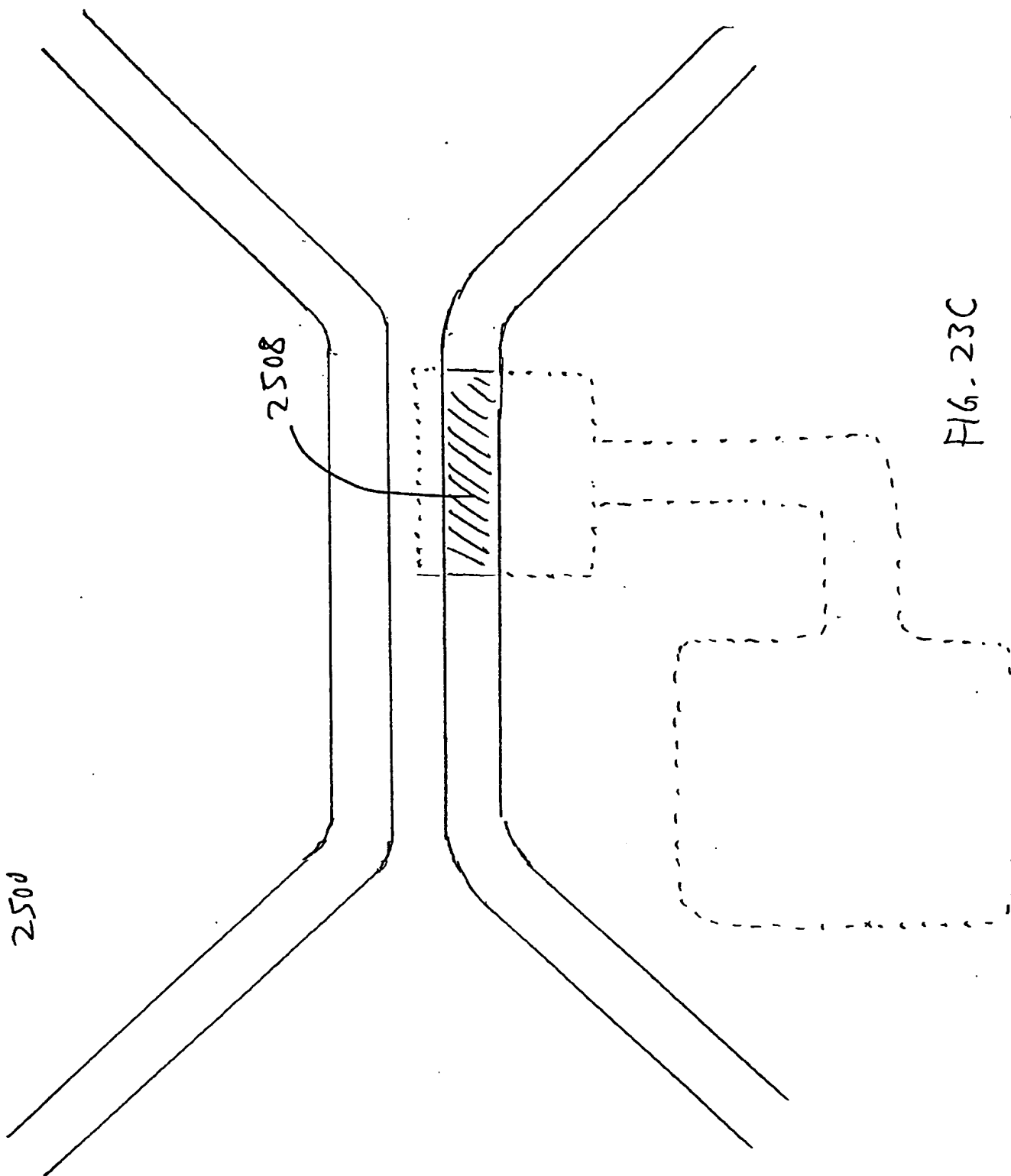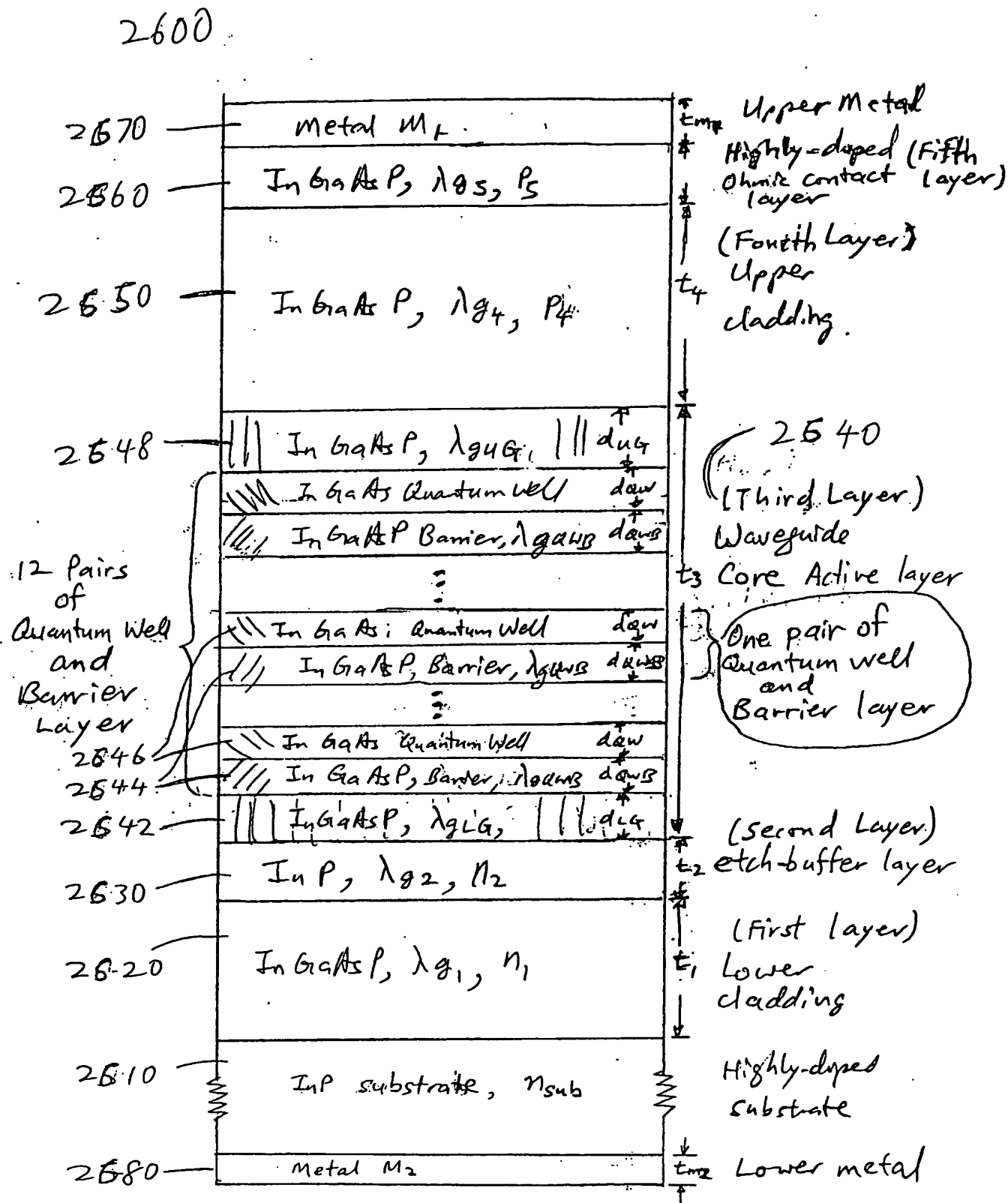
FIG. 24
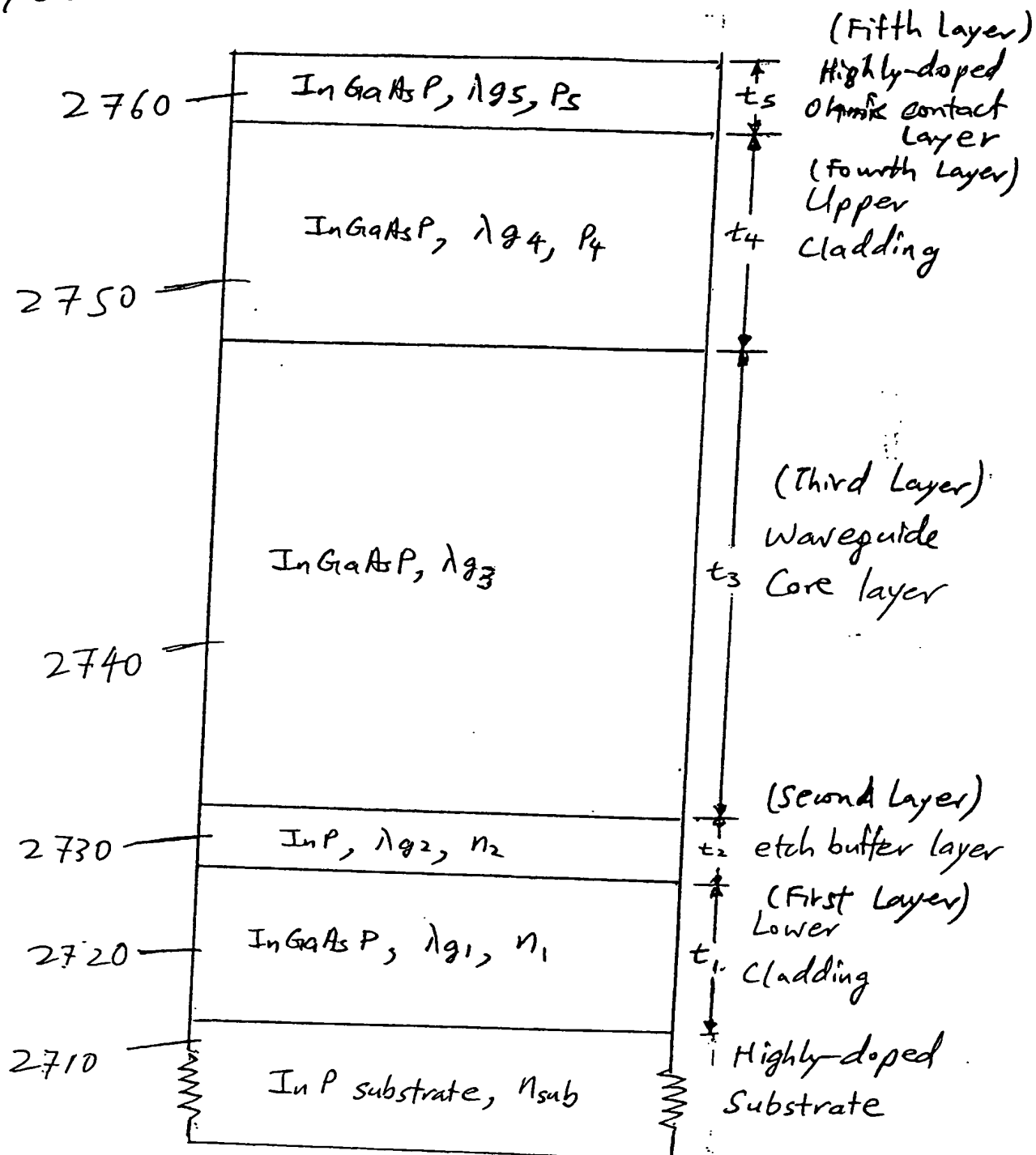
FIG. 25

E-Beam Lithography
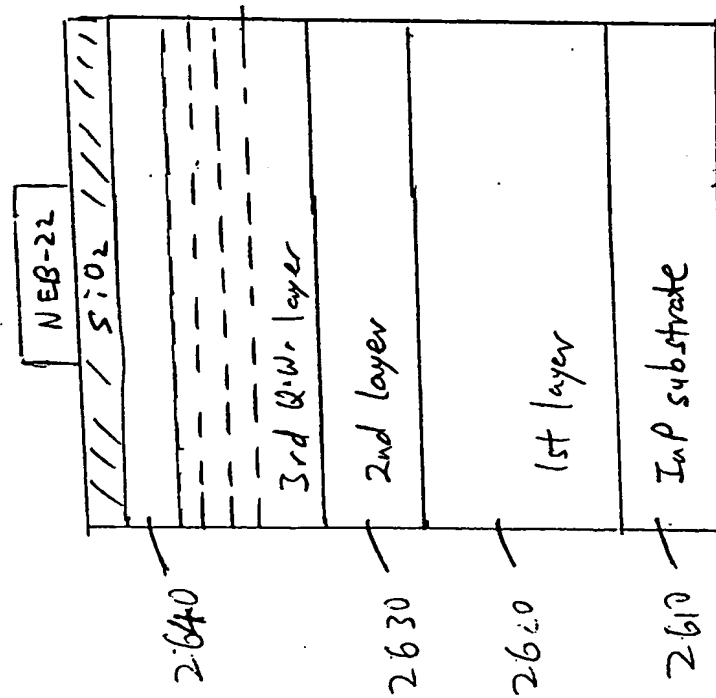
FIG. 26A

RIE
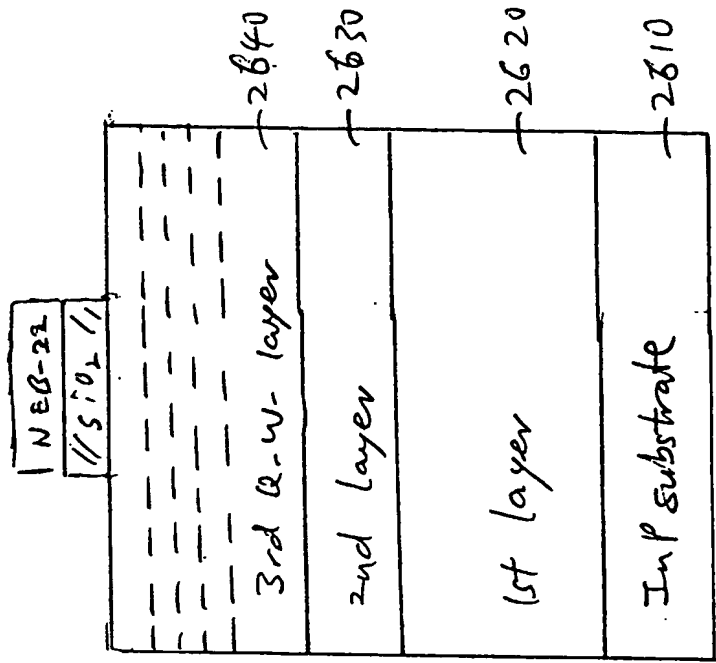
FIG. 26B

Dip into HF briefly to etch away
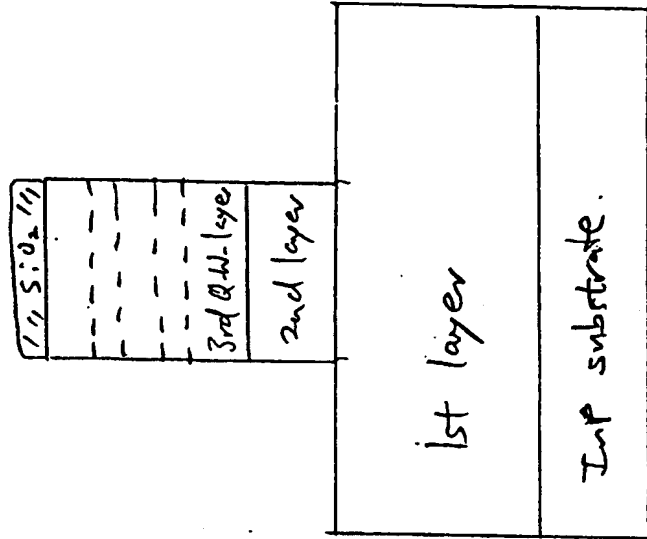Etched Buffer layer creating
a smooth surface for regrowth

//Si0₂ //

3rd QW layer

2nd layer

1st layer

InP substrate.

FIG 26D

InGaAsP Etching

//Si0₂ //

3rd QW layer

2nd layer

1st layer

InP substrate

FIG. 26C

1: Growth of upper
Cladding and Ohmic contact

5th layer	2760/2660
4th layer	2750/2650

3rd W.G. layer — 2640

3rd W.G. layer

3rd W.G. layer

3rd QW layer

2nd layer — 2740

2nd layer — 2730/2630

1st layer — 2720/2620

InP substrate — 2710/2610

FIG. 26F

Regrowth of transparent region

2640

3rd waveguide core layer — 2740

1:Si:02 1/1/

3rd QW layer

2nd layer — 2730

3rd waveguide core layer — 2740

2nd layer — 2730

1st layer — 2720

InP substrate — 2710

FIG. 26E

Waveguide A pattern

Waveguide B pattern

C

| | Si₃N₄ / SiO₂ | Si₃N₄ / SiO₂ | | |

2760/2660 — 5th layer

2750/2650 — 4th layer — 2640

2740 — 3rd WG layer, 3rd WG layer

2730/2630 — 2nd Layer

2720/2620 — 1st Layer

2710/2640 — InP substrate

E-beam writing of waveguide pattern and transfer of pattern down to SiO₂ mask

FIG. 26 G

Waveguide A

C

waveguide A

waveguide B

C'

Si₃N₄ — 2760 — 5th layer

2750 — 4th layer

2740 — 3rd layer, waveguide core

3rd Layer waveguide core

2740

2730

2720

2710

Si₃N₄ — 2660 — 5th layer

2650 — 4th layer

2640 — 3rd layer, waveguide core and quantum well

2630 — 2nd layer

2620 — 1st layer

2610

InP substrate

WA ↑↑↑↑ WB

Wg

waveguide A

waveguide B

FIG 26 H

Etching of InGaAsP with SiO₂ as a mask to form waveguide A & B

BCB curing and etching

SiO_2

BCB

BCB

substrate

InP

waveguide B

waveguide A

FIG. 26 J

First BCB Planarization

SiO_2

BCB

InP substrate

waveguide B

waveguide A

FIG. 26.I

2nd BCB Planarization (BCB)

SiO_2

BCB

BCB

InP substrate

Waveguide A   Waveguide B

FIG. 26 L.

SiO_2 etching by HF.
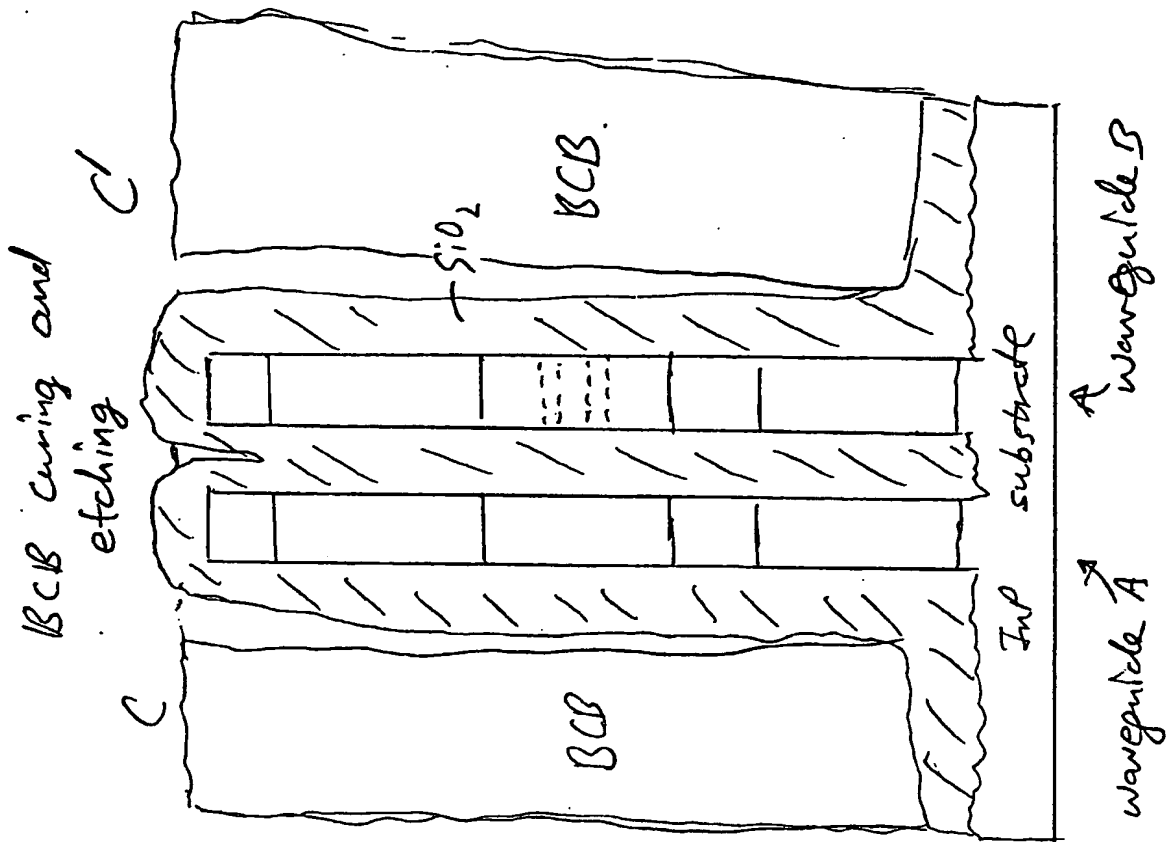
BCB

InP substrate

SiO_2

SiO_2

Waveguide A   Waveguide B
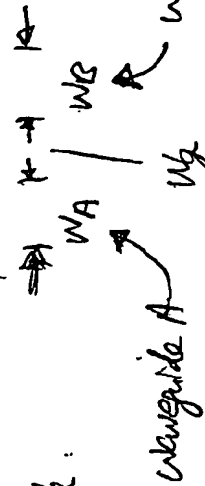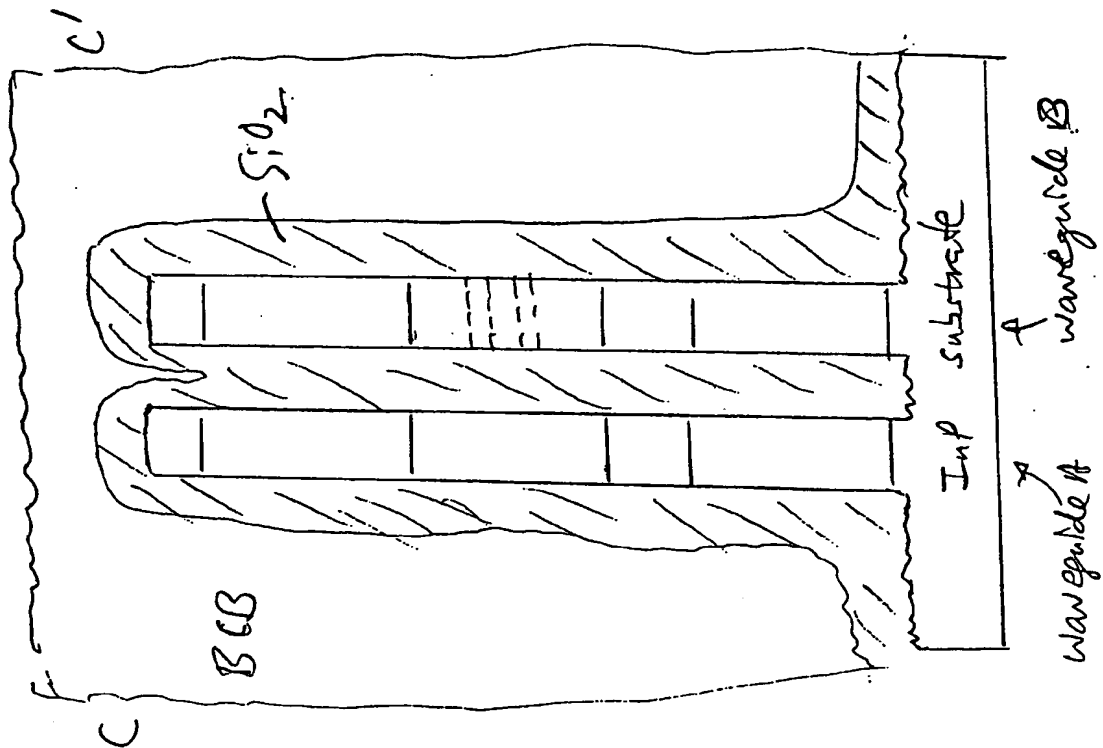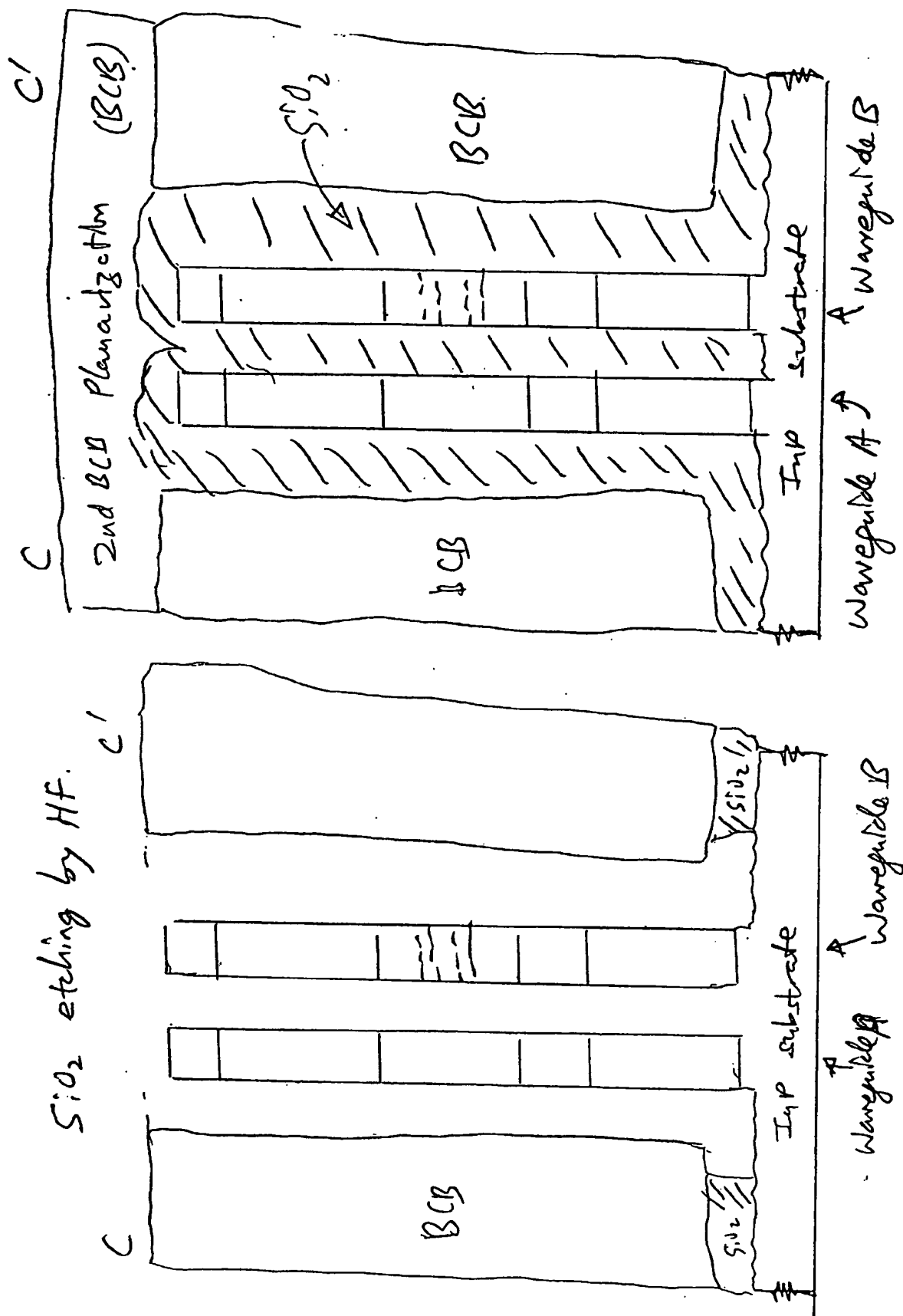
FIG. 26 K

After BCB etching by RIE
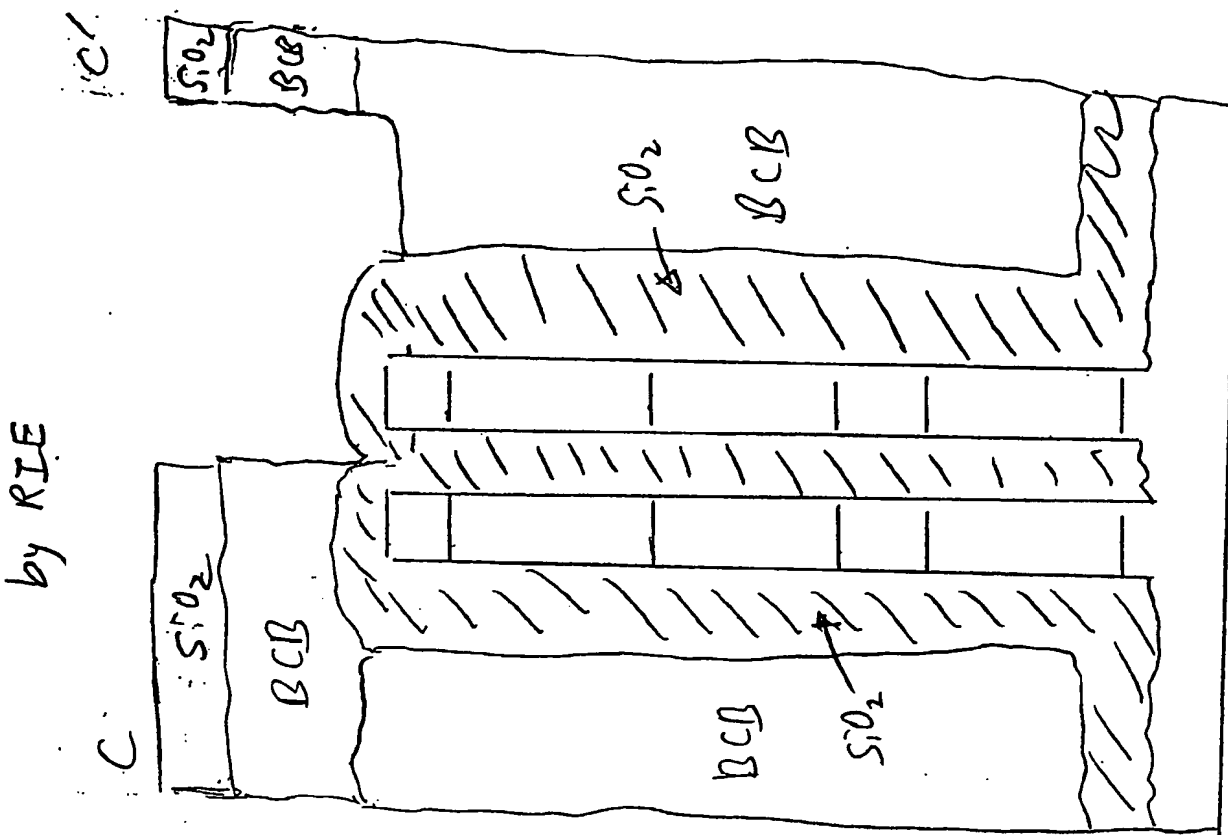
FIG. 26 N

Metal Mask Pattern

FIG. 26 M

deposition of metal contacts M_1 and M_2.

metal $(M)_1$

Photoresist

BCB

BCB

SiO_2

BCB

BCB

C

C'

InP substrate

metal M_2

FIG. 26 R.

RIE etching of SiO_2

C'

BCB

2660

BCB

SiO_2

BCB

BCB

SiO_2

C

InP substrate
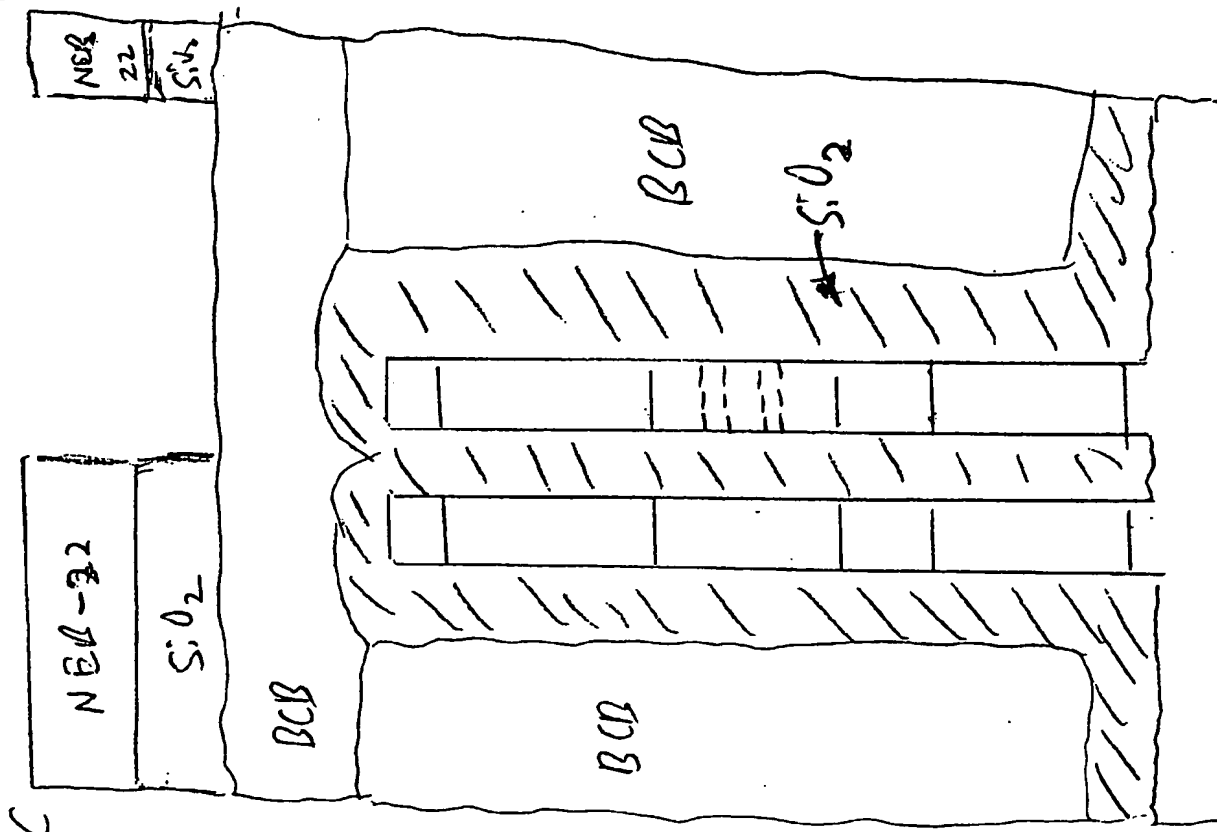
FIG. 26.0

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US00/25371

A.	CLASSIFICATION OF SUBJECT MATTER

IPC(7)   :G02B 6/26

US CL   :Please See Extra Sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   385/14, 15, 16, 17, 24, 39, 40, 42, 46, 130, 131, 132, 122; 437/129

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

USPTO APS EAST, search terms: (optic$ adj coupler$) and (quantum$ adj well$) and (nonlinear$ adj switch$)

C.	DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,878,181 A (VAN DER TOL) 02 March 1999 (02.03.1999), figs. 1-4 and col. 3, line 65 - col. 7, line 32.	1-4, 7-8, 11, 13-20
X	US 5,005,933 A (SHIMUZU) 09 April 1991 (09.04.1991), figs. 1-8E and col. 3, line 18 - col. 6, line 15.	31-34, 37-38, 41-46, 49-55
A	US 5,315,422 A (UTAKA et al) 24 May 1994 (24.05.1994), entire document.	1-67
A	US 5,887,092 A (VAN DER TOL) 23 March 1999 (23.03.1999), entire document.	1-67
A	US 5,703,975 A (MILLER et al) 30 December 1997 (30.12.1997), entire document.	1-67

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 DECEMBER 2000	28 DEC 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks	
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Washington, D.C. 20231	BRIAN HEALY
Facsimile No. (703) 305-3230	Telephone No. (703) 308-2693

Form PCT/ISA/210 (second sheet) (July 1998)★

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

385/14, 15, 16, 17, 24, 39, 40, 42, 46, 130, 131, 132, 122; 437/129